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Reducing pesticide use in orchards through environmental monitoring for pest protection

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Reducing pesticide use in orchards through environmental
monitoring for pest protection

by

Mahmoud Kamel Ali

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

Major: Horticulture

Approved:

Signatures have been redacted for privacy

Iowa State University
Ames, Iowa

1991

DEDICATION

This work is dedicated to my parents, Kamel and Ammoun for their unfailing support. It is also dedicated to my brother, Abdul-Kareem, with the Syrian troops in Kuwait for risking his life for the cause of peace.

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GENERAL LITERATURE REVIEW

Introduction

Two insect pests--apple maggot (Rhagoletis pomonella (L.)) and codling moth (Laspeyresia pomonella (Walsh))--and apple scab, a disease caused by the fungus Venturia inaequalis (Cke.) Wint., cause substantial economic losses for commercial apple growers in the North Central United States. Early recommendations for control of apple maggot and codling moth were the keeping of sheep, poultry, and hogs in apple orchards to destroy apple fruits as they fell, or hand-picking and destroying infested apple fruit (16, 34, 96). The amount of labor and the number of animals associated with these methods of control have made such practices impractical when large orchards are planted.

Synthetic chemical pesticides are more effective and practical tools for insect and disease control in apple orchards, and have been used extensively since World War II (34, 96). Increased sociological concerns and environmental risks associated with chemical control, as well as its economic cost, have led to the development of predictive models that make use of biological and climatic data in attempting to reduce pesticide sprays. In addition, monitoring of insect populations by means of traps can help to reduce the frequency of pesticide applications while maintaining satisfactory pest control (70, 71). Use of weather-based systems and pest population monitoring systems has been shown to reduce pesticide use and input costs, but has been slow to gain acceptance in Iowa and other apple-growing states in the North Central region.

Apple Scab

Chemical control of apple scab, which is a serious disease worldwide (57), is essential for the economic production of apples in many areas. To minimize losses from the disease, fungicide sprays are started in early spring at the green tip stage of bud development (77, 109) and continued through early summer and sometimes until harvest. An understanding of the life cycle of the pathogen is imperative if the pesticide usage is to be reduced while maintaining adequate control of the disease (1, 12, 29, 31, 50, 61, 74, 77, 110, 111).

Disease cycle

V. inaequalis overwinters in apple leaves that were infected during the previous growing season (3). Pseudothecia, the perfect-stage fruiting bodies, develop during the fall and early winter in infected leaves on the orchard floor, and undergo several stages of development (3). James and Sutton (55, 57) characterized the sequence of development in *V. inaequalis*. Initially, a stroma, a compact mycelial structure, forms under the cuticle of a fallen infected apple leaf. Within the stroma, hyphae coil under the cuticle to form pseudothecia, structures in which asci are formed. Next the ascogonium, the female gametangium, forms in the pseudothecia. The ascogonium then starts to disappear and pseudoparaphyses (structures that resemble sterile hyphae) start to appear and fill the inner open space of pseudothecia.

These pseudothecia then differentiate into asci (saclike cells) which eventually contain the ascospores (sexual spores). Formation of

asci is completed before the contents are differentiated. In the asci, ascospores are non-septate when first formed and later become septate and pigmented as they mature and are discharged from asci.

Ascospores mature during the spring and early summer (111). When the leaves are wet, ascospores are discharged into the air and are carried to the leaves and fruit to initiate the primary disease cycle (3, 27, 29, 30, 111). On the leaf or fruit surface, ascospores germinate only if moisture remains on the surface for a sufficient period of time (3). A germinating ascospore produces an appressorium (swollen tip of a hyphae) from which a mycelial tube penetrates the cuticle. The fungus secretes enzymes (and possibly toxins) that break down macromolecular components of the cell into small molecules that can be absorbed by the mycelium. After 8 to 15 days of incubation, olive-green to black lesions with diffuse margins, appear on infected leaves or fruit. Conidia (asexual spores) develop in the lesions and are released from lesions when exposed to moisture for a sufficient period of time. Conidia then spread by rain splash or air currents to additional leaves and fruit, where they can germinate to initiate secondary cycles of the disease. Numerous secondary cycles may occur, causing successive periods of defoliation and fruit injury during a single growing season. After infected apple leaves fall to the ground, the mycelium begins to form pseudothecia to complete the life cycle (3).

Factors influencing pseudothecia development

Temperature, leaf moisture, time of leaf fall, cultivar, and time of infection are major factors affecting development of pseudothecia.

In the field, pseudothecia development is highly correlated with rainfall or high relative humidity (56). Ross and Hamlin (103) reported that low rainfall was the most important factor in limiting pseudothecia formation.

Temperature has a pronounced effect on pseudothecia development, rate of ascospore maturation, and number of pseudothecia produced per unit area of infected leaf (28). Temperature during the mid- to late-winter months has been shown to have a more pronounced effect upon pseudothecia development than temperature and rainfall during April and May (62) or temperature in October, November and December (57). Keitt and Langford (64) and Ross and Hamlin (103) found similar results when they studied the effect of temperature on pseudothecia production. Pseudothecia formation was profuse at 8 C, and was abundant but delayed at 4 C. Pseudothecia only occasionally formed at temperatures of 12 C, whereas no mature pseudothecia developed at temperatures of 15 C or above.

Time of ascospore discharge

Knowing the date of first ascospore discharge is of great value for timing of fungicide sprays. In New York, Szkolnik (111) found that no ascospores were released until about the tight cluster stage of apple tree development and that the peak of ascospore discharge was between the pink and petal fall stages. In other studies (30, 37), the timing of first

ascospore release in different climatic zones ranged from advanced green tip to bloom, and the peak of ascospore release from most locations was recorded from full bloom to petal fall.

Environmental factors influencing the maturation and discharge of ascospores

The duration of leaf wetness has a strong influence on the pattern of ascospore discharge by *V. inaequalis*. After sufficient duration of leaf wetting during daylight hours, ascospores may be released (10, 13, 30, 69). Brook (11) observed that discharge occurs only as long as there is a film of water over the pseudothecia. Fry and Keitt (25) also reported that water is the most important requirement for ascospore release. Many investigators have studied the effect of dew on ascospore discharge (11, 31, 79, 104). Gadoury and MacHardy (31) and Hirst et al. (50) did not catch any airborne ascospores when dew occurred without rain. However, they trapped ascospores when dew preceded or followed rain periods. In contrast, Moore (79) and Brook (11) found that dew could release ascospores.

Temperature has a marked effect on the rate of ascospore maturation (28). Gadoury and MacHardy (27) found that the maturation rate of ascospores increased as temperature increased from 6 to 20 C. Brook (13) concluded that the greater discharge of ascospores during daylight was due to the temperature effect on ascospore maturation, rather than to direct effect of light on discharge of spores. Gadoury and MacHardy (31)

reported that when pseudothecia were wet during daytime, ascospore discharge slowed whenever the temperature fell below 10 C.

Many researchers have concluded that ascospore discharge occurs primarily during daylight hours (1, 11, 31, 50). Gadoury and MacHardy (31, 69) found that during four rainy periods relatively few ascospores (4%) were released at night. Brook (11) reported that when the leaves were wet, the most important factor limiting ascospore discharge was light. He found that the ascospore discharge rate was higher in the afternoon than in the morning.

Patterns of ascospore and conidia release

The precise timing of ascospore discharge from leaves following or accompanying rain is not yet clear. Some ascospores were trapped 3 to 5 hours after wetting (62). In another study, a few ascospores were trapped during the first hour of rain regardless of the temperature (75). The peak of ascospore discharge was reported to occur between 3 and 8 hours after the start of a rain period (1, 75).

The asexual stage of V. inaequalis, Spilocaea sp., can produce large numbers of conidia very rapidly in foliar lesions during the growing season (110). These conidia, released by air currents or rain splash, are disseminated from tree to tree in the orchard, sometimes causing a massive inoculum buildup. Hirst and Stedman (48) concluded that, if moisture was present, airborne conidia were important in establishing the disease in orchards that previously had been scab-free. They also noted that the peak of conidia discharge occurred in early afternoon. Kumar and Gupta

(65) observed a peak of conidia release during rainy weather. However, they also caught substantial numbers of conidia in the air during dry weather.

The establishment of secondary scab infection requires somewhat different conditions of moisture and temperature than for primary scab infection. Under optimum conditions, ascospores induce infection more rapidly than conidia (80). Heuberger et al. (47) reported that under conditions of high relative humidity, temperatures above 35 C reduced conidia survival. At low relative humidity, temperature had no effect on conidia viability. Secondary scab infection, caused by conidia, requires a longer period of continuous leaf wetness (7 to 9 hours) than primary infection by ascospores (6 hours) (39, 80). Ascospores on current year's leaves may survive dry intervals 24 hours longer than conidia (80). Moore (80) found that infection by conidia or ascospores was not reduced substantially by dry intervals of 24 hours between wetting periods, but that dry intervals of 48 hours or more appreciably reduced infection.

Louw (1948), cited in Kumar and Gupta (65), observed a 50 percent reduction in conidia viability in 22 days at 0% relative humidity. However, when leaves were stored for 17 days at higher temperatures (20 and 30 C) at 0% R.H., no conidia were viable. When Kumar and Gupta (65) stored scab-infected leaves in a room in which temperature never exceeded 27 C and relative humidity was held at 64.1%, they observed 61% survival of conidia for up to 14 days.

Prediction of apple scab infection periods

Mills' system In 1944, Mills (76) recognized that primary and secondary infections do not occur unless certain conditions of temperature and duration of leaf wetness are met. For example, at 2 C, 30 hours of wet foliage are needed for infection to start, while at 13 C, only 9 hours of wet foliage are needed for infection to start. Based on experiments over a range of combinations of temperature and duration of leaf wetness, Mills constructed a chart, now known as the Mills Table, that could be used to determine whether or not an infection period had occurred. Mills asserted that wetting periods separated by dry intervals shorter than three hours should be considered to be a part of a single wetting period, and that dry intervals of 3 to 12 hours between wetting periods should be considered part of a single wetting period if the relative humidity remained above 90 percent. This system for identifying apple scab infection periods gained prominence after the advent of eradicated fungicides, which could effectively control disease even if applied one or more days after infection had occurred (10, 55, 56).

A microcomputer system About 40 years after Mills' work, other investigators programmed microcomputers to monitor temperature, leaf wetness, and relative humidity in apple orchards and to predict apple scab infection periods based on modified Mills Table criteria (60, 61, 63).

Further modification of Mills' system The Mills Table served as a first step toward the development of systems that used weather data to predict apple scab infection periods. However, the system was not without some limitations. Because they did not account for daylight effects in

interpreting field results, Mills and Laplante (77) concluded that ascospores require 3 more hours of wetting than conidia to infect leaf tissue at temperatures of 14 - 24 C. Recent laboratory studies have found that ascospores actually require 2.9 hours less wetting time than conidia for release in daylight (69, 105). Schwabe (105) confirmed results of MacHardy and Gadoury, finding that the minimum periods required for infection by conidia were longer than those for ascospores at all temperatures used in his studies (4.9, 9.1, 15, 19, and 23 C). Gadoury and MacHardy (69) found that ascospore release in darkness is insufficient to initiate many infections. They therefore proposed a revision of Mills' criteria for predicting apple scab infection periods. This revision accounted for daylight effects on the start of infection periods. Wetting periods occurring at night were not considered to be part of infection periods.

Codling Moth

Codling moth, Laspeyresia pomonella (L.), is a serious pest of apple in many apple-growing regions of the world. Cutright (21) stated that during the past hundred years codling moth has been, in almost all years, the most severe orchard pest in Ohio. Because of differences in weather conditions, the timing of events in the codling moth's life cycle differs from one region of the United States to another and studies made in one region may not be fully applicable to other regions (54).

Life cycle

The codling moth overwinters as a larva in a cocoon (21). Examples of overwintering sites include: beneath loose bark of apple trees, in splintered ends of broken branches, in cavities in trees, on old baskets on the ground, among weeds, in cracks in the ground, or in packing sheds (21, 43, 54, 106). In the spring, larvae develop into pupae, which are in turn transformed into adults. The moths emerge in early spring and mate within a few days of emergence. The female moth lays eggs on apple leaves and fruit a few days after mating. Eggs hatch into larvae that feed on the apple fruit, causing economic damage.

Studies of the life cycle of the codling moth have revealed much variation in the duration of each development stage. Emergence time in the spring differs from one region to another. In Ohio, emergence starts as early as May 1 and as late as May 31, with an emergence peak occurring from May 6 to June 5 (21). In Delaware, the first emergence was recorded as early as May 23 and as late as June 30, with emergence peaks occurring from May 29 to June 3 and from June 9 to June 17 (106). In Arkansas, emergence occurred between May 20 and May 31 (54). If temperature, rainfall and light conditions are favorable, egg deposition begins 3 or 4 nights after emergence (21). Eggs are laid on apple fruit and leaves (9, 21, 53). The average number of eggs laid per female varies from 45 eggs in Australia (33) to 59 eggs in Michigan (54). Eggs hatch 8 to 13 days after oviposition in Ohio (21), 6 to 7 days in Michigan (44), 7 days in Australia (33), and 10 to 12 days in Washington (115). The young larvae that hatch from eggs laid on leaves wander about until they find fruit on

which to feed. On fruit, the larvae bore to the center, where they feed on the seeds, then cut channels to the outside and drop to the ground if the fruit has not dropped yet (54). For the next 2 to 3 weeks, the larvae seek a place to spin a cocoon, then enter the pupal stage (21). In Delaware, the duration of the pupal stage was found to be 25 days on the average (106). The pupae give rise to moths which feed for 3 to 4 days, mate, lay eggs, and die. The number of generations per year is governed by weather conditions. Thus, the codling moth may have a different number of generations in different climatic regions. The number of generations per year was found to be 4 in Arkansas (54), 2 to 3 in Australia (33), 3 in Illinois (37), 1 in Maine and Virginia, 1 to 2 in Massachusetts, 2 in New York and California, 2 to 3 in Delaware, and 3 to 4 in Georgia (113).

Effect of environment on development and activity of codling moth

Environmental factors strongly affect the development and activity of the adult codling moth, and the severity with which the larvae infest apple fruits. Borden (9) reported that light intensity, temperature, humidity, and wind govern the activity of the adult codling moth. He stated that there may be no flight at all when the temperature is below 12 C or above 25.5 C, or when it is too windy.

Temperature has a marked effect on the time and rate of pupation (21, 43, 106). In Ohio, Cutright (21) found that the length of the pupal stage may vary from 10 to 20 days depending, at least in part at least, on temperature. The duration of each developmental stage is highly influenced by temperature (21, 43, 54, 114). Egg laying does not start if

the temperature is below 17 C (21, 54) and the rate of egg deposition increases with rising temperature up to 29.5 C (21, 38). In Arkansas (54), it was found that an increase in temperature tends to increase daily oviposition, and years of relatively high temperatures have been associated with heavy infestation (54). However, when temperatures rose above 27 C, oviposition declined gradually until it almost ceased at temperatures of 31 C (54). Depending on the temperature, the length of the incubation period was reported to be 8 to 13 days in Ohio (21), 4 to 15 days in Illinois (37), 6 days in Michigan (43), and 6 to 7 days in Delaware (106) and Arkansas (54).

Cutright (21) found that, as temperature increased from 18 C to 29.5 C, young larvae enter and establish in the fruit in proportionately greater numbers. Glenn (36) found that the length of the larval period ranged from 18 to 45 days in Illinois. He attributed this variation in larval period duration to climatic conditions, especially temperature.

Selkregg (106) found that the pupal period of individuals pupating late in a growing season was shorter than that of those pupating early in the season due to higher temperatures. Glenn (36) found that the pupal period varied from 7 to 46 days, depending on weather factors, of which temperature was most influential.

Relatively heavy infestation of apple fruits by codling moth has been reported to occur in dry years (21, 41, 54, 114). Hagely (39) showed that rainfall during late spring and early summer significantly reduced insect entries into fruit.

However, temperature may not be the only factor affecting pupation. The potential influence of humidity and wind on the activity of the codling moth has not been investigated thoroughly. There is some evidence that insect entries are higher when relative humidity is comparatively low and the wind was strong (9, 21). Cutright (21) reported that the infestation was far more severe in orchards on ridges, where humidity was relatively low, than on valley floors, where humidity was higher.

Spray timing for control of codling moth

For the most cost-effective control of codling moth, it is important that insecticide applications be timed to coincide with the period of greatest emergence of the larvae (44). To determine the period of greatest emergence, trapping and the degree-day models have been used.

Traps Using different types of traps, many researchers have attempted to determine the optimum time at which insecticides should be applied. For this work, female pheromone (chemical sex attractant) have been used frequently. In 1972, an experiment relating synthetic pheromone-baited trap catches to seasonal infestation level was conducted in a variety of apple orchards in Michigan by Riel and Croft (100). They reported that cumulative trap catches from the first few weeks of the growing season correlated well with final infestation levels, suggesting that pheromone traps could be used as a predictive tool. However, cumulative trap catches were not correlated with infestation levels when cumulative catches exceeded about 100 moths per trap.

Riel et al. (101) undertook a study in 1973 to define the relationship between synthetic pheromone-baited trap catch, emergence, and oviposition for the two-generation climate in Michigan. They found that the efficacy of trapping was highest at the beginning of spring flight, but dropped off with increasing oviposition activity. Competition between traps and feral female moths was suggested to be the major factor contributing to the high variability in trap efficiency during both generations. In British Columbia, Madsen and Vakenti (71) reported on the use of traps baited with synthetic pheromone to monitor codling moth populations in six commercial apple orchards. The density varied from 1 trap per 0.4 hectare in 1973 to 1 trap per hectare in 1974. They sprayed only when the traps within the orchard captured two or more moths per trap per week during two consecutive weeks. Using this criterion, they obtained a 43.1% reduction in the number of required sprays for codling moth control over a 2-year period compared with a traditional spray program. The insect injury level to apple was less than 1% in all but one orchard.

In Ontario, Madsen (70) evaluated the potential use of synthetic pheromone baited traps in apple orchards. He placed one trap per 0.4 hectare and sprayed if male moth captures exceeded two per week in any trap. Using these criteria, only one spray was required instead of a traditional schedule of three applications, and the infestation level at harvest was less than 0.5% in treatments using traps. Rock et al. (102) evaluated trap catches with Codlemone (trans-8, trans-10, dodecadien-1-01, a synthetic pheromone of L. pomonella, (Zoecon Corp., Palo Alto, Calif.))

versus "automatic" (pre-scheduled) treatments for codling moth control in a North Carolina apple orchard. In the trapping treatment, they sprayed only if more than two moths per trap were caught during two consecutive weeks. The traditional spray schedule in North Carolina used 3 to 11 postbloom sprays for codling moth control. The trapping treatment used 3 to 6 postbloom sprays and the infestation level at harvest was 1% or less. They suggested that, using this method, 3 to 4 postbloom sprays in most North Carolina apple orchards would provide economic insect control.

In British Columbia, Madsen and Vakenti (72) used traps baited with Codlemone and visual detection of fruit infestation to determine whether and when to spray. They sprayed only when one of the following criteria was met: 1) traps placed along borders of the orchard, at a density of one trap per 0.4 hectare (1 acre), captured an average of more than two moths per trap per week, and infested apples were found; or 2) traps within the orchard captured an average of two or more moths per trap per week, and infested apples were found. Using these criteria, one to two insecticide sprays were sufficient to give satisfactory control instead of the three sprays usually applied. They concluded that traps baited with synthetic codling moth sex attractant can be useful in estimating population level and determining the need for chemical sprays. In another study, female-baited and synthetic pheromone (trans-8 trans-trans-10-dodecadien-1-01) traps were compared as population indicators (71). Over most of the season, the synthetic pheromone traps captured far more codling moths than those baited with virgin females.

Degree-days Thermal unit accumulation is another method used to determine when to spray for codling moth control. Many workers have studied the development of the codling moth in relation to heat unit summation in an attempt to time insecticide applications to coincide with the period of greatest larval emergence in the orchard. The degree-day, a widely used unit of heat summation, is calculated in a number of alternative ways. A commonly used formula for calculating degree-days (DD) is as follows:

$$(I) \text{ DD} = [(\text{daily maximum air temperature} + \text{daily minimum air temperature}) / 2] - \text{base temperature.}$$

In Washington (2), degree-days were accumulated from a starting date of March 1. Degree-days were determined using equation (I), where minimum temperature was 10 C, maximum temperature was 31 C or less, and base temperature was 10 C. A cover spray was recommended after an accumulation of 450 DD and a second cover spray 21 days after the first one (21 days was the expected residual life of the insecticide used in this study). These two cover sprays were intended to control the first generation of the insect. A single cover spray was recommended for the first generation after an accumulation of 560 DD only if sources of codling moth infestation external to the orchard were nil, and if no codling moth problem had existed within the orchard. For control of the second generation of the insect, a cover spray after an accumulation of 1460 DD was recommended, followed by another cover spray 21 days later. Where the

codling moth had been consistently controlled, these workers recommended only one cover spray after an accumulation of 1660 DD to control the second generation.

In New Jersey, Headlee (46) reported that degree-days can be satisfactorily used to determine the periods during which cover sprays should be applied. Headlee (45) showed that the degree-day summation is a satisfactory indicator of the time when insecticide application should be made.

Hagely (40) found that the period of greatest larval emergence occurred 6 to 10 days after first emergence and that emergence could be predicted DD accumulation. In 1971 and 1972, 144 and 137 DD accumulated from the date on which the first male moth was caught in a synthetic pheromone-baited trap to the date on which the first larvae emerged, respectively. Also, he found that an accumulation of 71 to 100 DD from the date of recovery of the first eggs could be used to determine the period during which larval emergence would probably occur. This model combined synthetic pheromone-baited trap captures with phenology of the insect. Beers et al. (8) described a similar model for the control of codling moth. They used synthetic pheromone-baited traps to establish a biofix (a date on which the accumulation of degree-days starts), at which degree-day accumulation was begun. The first cover spray was applied after 250 DD had accumulated. The first cover spray was targeted at newly hatched larvae. A second cover spray was applied 21 days later (21 days is the residual life of azinphos-methyl, the insecticide used). A third cover spray when 1260 DD's (after the biofix was established) were

accumulated, and a fourth spray 21 days later were targeted for the second generation of emerging larvae. Using the above model, Beers et al. obtained satisfactory control of codling moth in Washington State apple orchards.

Apple Maggot

The apple maggot, Rhagoletis pomonella (Walsh), is a serious insect pest of apples. The larval stage of a fly, the apple maggot is native to northeastern United States and Canada (33, 109). It has spread from there to southern, central, and eastern states of the United States (63, 89).

Life cycle

The life cycle of apple maggot is strongly affected by environmental factors. The number of generations, time of emergence, and severity of the damage it causes vary among apple growing regions. In general, apple maggot has one generation per year (16, 63). It spends winters as a pupa in the ground and emerges as an adult fly in mid-June to early September (16, 34, 63, 81, 98, 107). The timing of emergence may vary considerably depending on temperature, rainfall (63, 73, 81, 93), and sunlight (83). When females emerge, their ovaries are undeveloped, and 7 to 14 days elapse before they start to mate and then lay eggs (63, 83, 86). Females deposit a single egg beneath the skin of a maturing apple (one egg per apple) (16, 34, 98); each female may lay about 300 eggs over her life span (63, 83, 87). Depending on the temperature, the eggs hatch 2 to 10 days after deposition (63, 83). The larvae feed within the apple, making

tunnels throughout the flesh. These tunnels result in misshapen fruit and internal discoloration, which cause economic losses (16, 33, 34, 83).

Larvae undergo three growth stages, and larval development is often completed in 20 to 30 days (16, 33, 34, 83). However, Davis and Jones (22) reported that larval development can be completed in about two weeks in Utah. Larval development rate may vary considerably from year to year and by geographic locations depending on weather conditions (44, 67).

When larval development is completed, larvae leave the fruit and enter the soil (16, 22, 34). Five days later the larvae develop into pupae (81).

Most of the flies emerge the following spring. However, some may require two or three years to emerge (16, 21, 73, 108), and others may emerge a few months after pupation (34, 73, 108).

Factors affecting development of the apple maggot

Several factors determine the timing of development and emergence of apple maggot flies. Phipps and Dirks (91) found that time of emergence was governed by rainfall, nature of the soil, cultivar, and geographic location. They found that two generations per year emerged where soils were light and one per year where soils were heavy. They also reported that only larvae which developed in early-maturing cultivars transformed to flies in the same season. Oatman (88) found that apple maggot flies emerge relatively early in the season and over a relatively short span of time when temperature is high and rainfall is low. He also reported that adults tended to emerge earlier, reach a peak sooner, and have shorter emergence periods if the larvae developed in early-maturing apple

cultivars than in late-maturing cultivars. Neilson (82) and Lathrop and Dirks (67) found temperature to be the limiting factor for the emergence of apple maggot flies.

Spray timing for control of apple maggot

Measures to control apple maggot differ from one region of the United States to another. However, the control strategies have some elements in common. Applications are aimed at controlling the fly stage. In many areas, apple maggot is currently controlled by applying insecticides on a protectant basis with sprays commencing 7 to 10 days after adults have emerged and continuing at 10- to 14-day intervals thereafter until harvest (32, 87, 98, 99, 112). If monitoring apple maggot adults could effectively detect the presence of these flies, insecticide applications could be used only when necessary rather than on a protectant basis (68). Two monitoring methods, traps and degree-days, have been tested in recent years.

Traps Since 1943, when Hodson (51) suggested the use of traps to monitor apple maggot activity, different types of traps and lures have been tested in the United States and other countries. Adult fly activity has been monitored with liquid bait traps (50), sticky bait traps (51), and noting first emergence of flies from ground caves (67). Reissig and Tette (97) and Neilson et al. (86) reported that baited, yellow, sticky Pherocon AM traps (Zoecon Corp., Palo Alto, CA) impregnated with ammonium acetate were sensitive enough to detect small populations of apple maggot, because flies were captured even when only trace amounts of fruit were

infested. They concluded that the traps could be used successfully in New York to determine the timing of apple maggot control sprays. Neilson et al. (87) stated that apple maggot adults were strongly attracted to yellow rectangles which, when coated with Stickem (a mixture of polymerized butene, isobutene, and butane) or Bird Tanglefoot (Zoecon Corp., Palo Alto, Calif.), make an excellent trap. He observed that these traps could capture adults within one day of emergence, and therefore could be used to provide reliable information on the timing of apple maggot sprays.

Prokopy (94) obtained a high degree of apple maggot control when using Sticky Red Sphere traps, wooden spheres painted with Tartar Dark Red enamel and coated with Bird Tanglefoot, (Sherman-Williams Co., Cleveland, Ohio) to determine timing of insecticide sprays.

Several types of traps have been tested for relative efficiency in detecting emergence of apple maggot flies. Burief (15) tested yellow-board traps (Sunflower enamel, Dean and Barry Co.), and red sphere traps (a red artificial apple, covered with Bird Tanglefoot and baited internally with a 5% ammonium acetate solution) and found that they were about the same in detecting emergence. Trottier et al. (112) compared the performance of two types of traps, Sectar pull-down [baited with 0.5 g HyCase (protein hydrolase) plus 0.5 g ammonium acetate mixed with a nondrying adhesive] and Pherocon ICPY- yellow (baited with 5% soy hydrolysate plus 50% ammonium acetate in a vial). They found no significant differences between these traps in the dates of first catch. Maxwell (73) found that Tanglefoot traps were more efficient in catching apple maggot than hydrolysate bait lures. Neilson et al. (87) compared

the effectiveness of Rebell traps [fluorescent yellow plastic rectangles 14 x 20.8 cm, precoated with a baited sticky adhesive, (Swiss Federal Res. Stn., CH-8820 Wädenswil, Switzerland)], Pherocon bait traps, traps with some artificial attractants, (weather-resistant yellow cardboard rectangles, 14 x 23 cm, protected with a baited sticky adhesive from Zoecon Corp.), and Sticky Red Spheres. They found that bait traps were the most suitable to determine spray needs.

Reissig (97) evaluated the following traps: 1) A yellow gypsy moth-type trap (consisting of a paper box with a 50-mm opening on each side and baited with a 5% yeast hydrolysate and 50% ammonium acetate solution), 2) a yellow sector insect trap (Zoecon Corp., Palo Alto, Calif) containing the same bait as the gypsy moth trap, 3) a sticky yellow card, the same type as the yellow sector trap, coated with a gram of HyCase and ammonium acetate mixed in the adhesive, 4) red plastic spheres coated with Bird Tanglefoot, and 5) a baited apple trap (a red artificial apple covered with Bird Tanglefoot that was baited internally with a 5% ammonium acetate solution). He ranked those traps in order of decreasing effectiveness as follows: baited apple, red plastic sphere, yellow card, sector, and gypsy moth trap.

Trap placement in orchard In an attempt to determine the optimal arrangement of traps in an orchard, Reissig (96) tested the performance of apple maggot traps in various apple tree canopy positions in relation to canopy radius, height above ground, and compass direction to compare their effect on the performance of three types of apple maggot traps: yellow sector, sticky yellow card, and red plastic sphere. He

found that all three types of traps caught the most apple maggot flies when they were placed high in the tree. Traps 1.2 m above ground were ineffective compared to those at heights of 2.0 or 3.0 m. Traps in the middle of the canopy radius caught a significantly higher average number of flies per trap than near the outside of the canopy. Reissig concluded that the effectiveness of traps varied according to their location within an apple tree canopy and that the effect of each location variable was different for each of the three types of traps. Similarly, Drummond et al. (23) found that the position of traps in a tree has a large effect on the number of flies captured per trap.

Degree-days Temperature has a pronounced effect on the development of apple maggot as well as other insects. Below a specified temperature, the development of insects does not proceed (67, 91, 97). Reissig et al. (99) found that the minimum temperature threshold for the development of apple maggot pupae was 6.4 C. They also reported that the best prediction of fly emergence was accomplished by accumulating degree-days from March 1 using 6.4 C as the developmental temperature threshold.

Accumulated thermal units, or degree-days (DD), have been used to predict the seasonal development and subsequently the spray timing of apple maggot (66). The DD threshold at which the first flies emerged ranged from 561 to 689 DD, depending on the location and the year (99). Deviation between observed emergence and the date on which the average DD threshold has ranged from -5 to 8 days (100). Trottier (112) found that the first significant catch of apple maggot occurred after accumulation of 800 DD above 9 C after April 1.

Laing and Heraty (66) compared predicted emergence of apple maggot flies, using DD accumulation with actual trap catches in the field. They found that use of DD for predicting emergence was only slightly more accurate than the use of calendar date. They found that the average value of DD accumulation until first emergence, using 6.4 C as a threshold and March 1 as a starting date was 638 ± 60 , which was within the range found by Reissig et al. (99).

SUMMARY

There is a strong relationship of pseudothecia development of Venturia inaequalis in fallen, infected apple leaves with temperature, leaf wetness and cultivar.

Environmental factors such as temperature, rainfall, and light act together to determine the rate of maturation and discharge of ascospores and conidia. By monitoring temperature and the duration of periods of leaf wetness, infection periods can be predicted. Such a disease-predictive system can be used to time fungicide sprays effectively and thereby to control scab while reducing spray frequency and economic cost.

Although apple scab has been investigated intensively, few workers have investigated the survival of ascospores once they are released. This aspect of the disease merits further study.

The life cycle of codling moth, including effects of temperature, light, and rainfall on codling moth phenology, have been investigated in some detail. However, the possible influence of relative humidity and wind on timing of the life cycle have received less attention.

Satisfactory control of codling moth can be achieved using pheromone traps to detect adult emergence and guide the timing of subsequent insecticide applications. However, much variation in degree-day threshold has been found from one year to another, suggesting that this area is in need of further research. A model combining pheromone traps (to establish biofix) and the degree-day model can also be used to achieve satisfactory control of codling moth (8).

The life cycle of apple maggot, the relation of temperature to insect development, and the effect of apple cultivar on infestation have been investigated. However, effects of certain environmental factors, such as rainfall, relative humidity, light, and wind on the timing of the life cycle remain poorly understood.

Traps for apple maggot, such as the yellow board and red sphere types, have been found to be effective enough to detect the presence of apple maggot flies in apple orchards and to determine the timing of subsequent insecticide applications. Control obtained by this method has been equivalent to traditional spray timing strategies, with fewer sprays.

The wide discrepancy between actual emergence of flies (determined by trap capture) and predicted emergence (determined by degree-day accumulations) calls into question the value of current degree-day models for determining spray timing for apple maggot.

PART I. REDUCING PESTICIDE USE IN ORCHARDS THROUGH
ENVIRONMENTAL MONITORING FOR PEST PROTECTION

INTRODUCTION

Spray schedules currently used by apple growers in Iowa, and in most other Midwest states, are based primarily on developmental stages of foliage and fruit, with little or no consideration of environmental conditions. Activity of many diseases and insects is determined to a large degree by certain environmental conditions--temperature, relative humidity, light, duration of periods of leaf wetness, and others (9, 21, 68, 76, 91). Whether or not weather poses a significant risk of pest problems, Iowa orchardists apply pesticides on a predetermined schedule. As a result, pesticides are often applied when they are not needed. Therefore, time and money are wasted and the environment may be needlessly contaminated.

Utilizing the known linkages between pest development and weather variables exemplifies an approach to pest control known as Integrated Pest Management (IPM). In IPM, pesticides are applied only when weather or pest populations pose a significant risk of pest outbreaks (60, 61, 63). This approach can save time and money, and reduce pesticide pollution of the environment.

Growers are most likely to adopt IPM-based methods if they are convinced that: 1) they can substantially reduce the number of pesticide sprays they apply, without sacrificing yield or fruit quality; 2) the methods are easy to use; and 3) profits are equal to or greater than from a traditional spray schedule.

The primary objectives of this study were:

1. To compare the ability of IPM-based spray programs for control of three major apple pests in Iowa--apple scab, codling moth and apple maggot--to reduce pesticide applications while maintaining yield and fruit quality equivalent to that of a "traditional" spray program.

2. To compare the spray strategies in an economic analysis. The purpose was to assess the economic attractiveness of IPM-based programs in comparison to current grower practice.

MATERIALS AND METHODS

Field Experiment and Treatments

This study compared pesticide spray strategies based on monitoring of the weather and pest populations with a "traditional" spray program for control of three apple pests: apple scab, codling moth and apple maggot.

The experiment was conducted in a 0.4 hectare (1 acre) planting of 7-yr-old apple trees (cv. Red Delicious), grafted on twenty different rootstocks, at the Iowa State University Horticulture Research Station, Ames, Iowa. The spacing was 3.65 x 5.50 m. The experimental design was a randomized complete block with five treatments of four replications each. The rootstocks were randomly distributed within treatments. Because of differences among rootstocks, tree size varied widely within a replication. In May, 1989, in order to minimize the variability in tree size caused by the different rootstocks, five trees were selected from the 10 or 11 trees in each replication on the basis of similar size and fruit set in 1989. Data were taken from this subset of five trees per replication during both years of the experiment.

During 1989, drought conditions (18) prevented the development of apple scab in the test plot. To provide overwintered inoculum for apple scab in 1990, several hundred kg of scab-infected apple leaves were brought from orchards in Missouri, Illinois and Michigan and spread evenly on the orchard floor on December 1, 1989. These leaves were chopped with a flail mower to minimize removal by wind.

In 1989 and 1990, pherocon traps (Great Lakes IPM, Vestaburg, MI) were used for codling moth and pherocon AM, and disposable stick sphere traps (Great Lakes IPM, Vestaburg, MI) were used for apple maggot. Traps were installed in the center of the plot at a rate of one trap per 0.8 hectares (2 acres). Codling moth traps were installed on April 27 and May 3 in 1989 and 1990, respectively. Apple maggot traps were installed on June 6 in both years. The sex pheromone cap for codling moth trap (placed in the center of the trap) was replaced at 4- to 6-week intervals. The traps were checked every other day until the biofix was established, and weekly afterwards and the number of moths and maggot flies caught were recorded (Fig.'s 1 and 2). The trap data were used to determine the need to apply insecticide sprays for treatments 1, 2, 4 and 5 (described below). To provide a large sample of insect populations, the average trap captures were monitored in the test plot and in another block of apple trees (cv. Chieftain) about 0.2 km distant.

A tractor and a hydraulic sprayer were used to deliver foliar applications of pesticide solutions at a rate of 1900 L per hectare (200 gallons per acre) (see Appendix, Tables A1 and A2, for timing and rates of pesticides used).

Treatments

Treatment 1 In 1989, this treatment utilized an electronic predictive system called a Predictor (Reuter-Stokes, Twinsburg, OH). The Predictor contained programs to predict the risk of apple scab and to accumulate degree days. It was located approximately 1.5 m above the

ground in a gap of about 3 meters between two adjacent trees in a row near the center of the test plot. Relative humidity and temperature sensors were located on the Predictor unit, and the wetness sensor was attached to a lower branch of an adjacent apple tree, beneath the tree canopy. The Predictor interpreted the weather data with built-in computer programs based on the Mills Table (7) and a degree-day calculator. It output the following data via pushbuttons: current apple scab infection risk, fungicide spray recommendations, and degree-day accumulation for codling moth and apple maggot.

In 1990, a CR-10 Measurement and Control Module (Campbell Scientific, Logan, UT), an automated datalogger, replaced the Predictor because the Predictor was no longer manufactured after 1989. Two leaf wetness sensors were positioned one meter above the ground near the CR-10 and oriented with sensor plates tipped 20 degrees to the north. A relative humidity/temperature sensor was installed nearby at the same height. The CR-10 was programmed to input data from the sensors at 5-minute intervals and to output the following data summaries at 2-hour intervals: temperature, relative humidity, and duration of periods of leaf wetness. Every two days, output was relayed from the CR-10 to an IBM-compatible microcomputer at Iowa State University via a telephone line and modems. The data obtained from the CR-10 were used together with a modified Mills table (7) to predict the risk of apple scab infection and to determine subsequent sprays for the disease.

For this treatment, in 1989, weather data and spray recommendations for apple scab were assessed every other day after the first week of

April. After pre-and post-bloom sprays, which were applied simultaneously to all treatments, no insecticide sprays were applied until two criteria were met: first, an average capture of two or more codling moth adults per trap per week or one apple maggot adult in any trap; second, the accumulation of degree-days to threshold values. For codling moth, these thresholds were 550 degree-days for the second generation of codling moth from March 1 and 1550 degree-days for the third generation of codling moth since March 1 (2). For apple maggot, the threshold for the second generation since March 1 was 1137 degree-days. Degree-day accumulation was continuously determined by the Predictor.

In 1990, spray criteria for codling moth were modified. Pheromone traps were used to establish a biofix date, the date of first sustained moth capture, on which degree-day accumulations were to be started (8). After the biofix was established, the DD threshold was 250 degree-days for the second generation and 1260 degree-days for the third generation of codling moth. When 250 degree-days accumulated after the biofix, the first cover spray of phosmet insecticide was applied. Additional cover sprays were applied at two-week intervals after the first cover spray, only if an average of 2 codling moths per trap were caught for the two consecutive preceding weeks. Another cover spray was applied when 1260 degree-days were accumulated after establishing the biofix, and at 2-week intervals for 4 weeks thereafter, only if an average of 2 codling moths were caught per trap in 2 consecutive weeks.

In 1990, degree-days for codling moth and apple maggot were determined using the maximum and minimum air temperature obtained from the strip chart (treatment 2 below).

Treatment 2 A Leaf Wetness Recorder (Belfort Instrument Co., Baltimore, MD), a strip chart recorder that continuously records temperature, duration of leaf wetness and relative humidity, was placed about 5 meters from the Predictor. The chart data were interpreted with a modified Mills Table (7) to determine whether an infection period for apple scab had occurred. The criteria for spray recommendations for apple scab and apple maggot were the same as in treatment 1 during both years.

Insecticide applications in 1989 followed the same criteria used in treatment 1. The degree-days were calculated using the strip chart data and applying the following equation:

(I) $DD = \{[(\text{maximum air temperature} + \text{minimum air temperature})/2] - \text{base temperature}\}$. Base temperatures were 10 C and 6.1 C for codling moth (2) and apple maggot, respectively. Temperature below these base temperatures halted development of the pests. When the maximum temperature exceeded 32.2 C, the maximum temperature was considered to be 32.2 C because development of codling moth and apple maggot does not increase with higher temperature over 32.2 C (2). When the minimum temperature was below the base temperature, the minimum temperature was considered to be the base temperature. In 1990, spray criteria for codling moth and apple maggot were as in treatment 1.

Treatment 3 This treatment, termed the "traditional" pesticide spray schedule, reflected current grower practice in Iowa. The fungicides

and insecticides were applied according to the 1989 and 1990 Iowa Commercial Tree Fruit Spray Schedules (Pm - 128), issued by Iowa State University Extension, and did not take account of weather conditions or pest populations.

Treatment 4 A "four-spray" spring fungicide spray schedule, designed and tested by Dr. Wayne Wilcox (Department of Plant Pathology, Cornell University, Geneva, N.Y., personal communication), was used for apple scab. This schedule entails applying a curative fungicide (see Appendix), at four predetermined stages of apple phenology: tight cluster, pink, petal fall, and first cover. Fungicides were not applied until tight cluster because recent evidence from New York orchards (W. Wilcox, unpublished data) indicated that overwintering inoculum of the apple scab pathogen is generally insufficient to cause an epidemic before this stage. In 1989, insecticides for codling moth and apple maggot were applied when trap capture threshold was met. In 1990, insecticides were applied as in treatments 1 and 2.

Treatment 5 No fungicides were applied (control). Insecticides were applied as in treatment 4 in order to insure harvestable fruit to fulfill needs of an ongoing rootstock trial.

Throughout the text, treatments will be referred to as Predictor (in 1989) or CR-10 (in 1990) for treatment 1, Leaf Wetness Recorder (LWR) for treatment 2, "traditional" schedule for treatment 3, "4-spray" program for treatment 4, and "no fungicides" for treatment 5.

Fruit and Foliar Damage Assessment

Assessment of fruit damage

Fruit damage due to insects and scab, and foliar damage due to scab, were determined after harvest. Fruit from each data tree were harvested separately, counted, weighed, and graded (using a commercial grading apparatus) to six sizes based on diameter of fruit (≥ 8.13 , 7.5, 6.88, 6.25, 5.63 and <5.63 cm). The fruit were examined individually and classified as marketable grade (no blemishes of any kind) or cull grade (fruit that had any blemishes). The cull fruit were then sorted by cause of blemishes (e.g., codling moth, apple scab, mechanical injury, other insects and other diseases). In both years, apples that had dropped from each data tree prior to harvest were collected, counted and evaluated to identify the source of injury (e.g., apple scab, codling moth, etc.).

Assessment of foliar scab

In mid-October, 1990, a composite sample of at least 100 leaves was taken from three terminal shoots in the interior of the canopy and three terminal shoots on the outer edge of the canopy of each tree. Apple scab incidence (mean percent of leaves with scab lesions per tree) and severity (average number of lesions per symptomatic leaf) were determined and analyzed for statistical differences (LSD, $P = 0.05$).

Economic Analysis

An economic analysis comparing treatment costs and returns was performed. Before the economic analysis was performed, several assumptions were made: 1) an amortization factor of 15% was set for the

weather-monitoring equipment (Predictor, CR-10, Leaf Wetness Recorder and Maximum/Minimum Thermometer) (M. Duffy, Department of Economics, Iowa State University, Ames, Iowa, personal communication); 2) lifetime of the equipment above was estimated to be 10 years (26); 3) time to spray a 0.4-hectare (one-acre) orchard with 201 apple trees was estimated to be 0.3 hour (P. Domoto, Horticulture Department, Iowa State University, Ames, Iowa, personal communication); 4) labor cost to operate the machinery, to monitor the instruments, and to calculate degree-days was calculated at \$6.00 per hour (M. Duffy, personal communication); 5) a single Predictor, CR-10 or Leaf Wetness Recorder was estimated to provide adequate monitoring for an orchard of up to 16 hectares (26); and 6) the fixed cost per 0.4 hectare (1 acre) for the tractor and the hydraulic sprayer for each spray was \$3.15 (M. Duffy, personal communication).

A partial budget technique was used to compare data from all treatments. An economic engineering approach was used to project yield, direct costs, and estimated differences among treatments over orchard sizes of 2, 4, 8 and 16 hectares. Direct costs included applying pesticides, monitoring pests, chemicals, machinery, labor, traps and monitoring equipment.

Revenue [(total marketable yield x price per unit weight) + (total culls x price per unit weight)] was determined and the return (revenue minus cost of control of scab and codling moth) was calculated for each treatment. Apple prices were obtained from the Iowa Agricultural Statistics Service (IASS), Des Moines, Iowa. Based on recommendations from the State Statistician at the IASS, 1987 apple prices were used to

determine revenue because they were more typical of the apple market than prices in 1988 or 1989. Wholesale prices per kilogram were as follows: \$0.85 for size 8.13, \$0.86 for size 7.5, \$0.84 for all sizes below 6.88 centimeters and \$0.32 for culls.

Pesticide retail prices for 1989 and 1990 were obtained from two different companies: United Suppliers, Inc. (Eldora, Iowa) and Brayton Wilbur Ellis Chemicals, Inc. (West Burlington, Iowa). The average price per unit was calculated and used in the economic analysis. Pesticide prices per kg were as follows: Nova, \$117.14; Benlate, \$34.69; Dithane M45, \$4.91; Dithane F45, \$8.21; Dikar, \$6.47; Imidan, \$8.18; Captan, \$0.78; and Thiram, \$1.39.

Cost and return were calculated for each study year and for both years combined. The following is an explanation of the steps that were followed to determine direct costs per treatment for each pest:

I. Machinery cost per season was equal to tractor and sprayer fixed cost per season per spray per 0.4 hectare (per acre), multiplied by the number of sprays per season and by the orchard size.

II. Labor cost was equal to the number of hours needed to spray, monitor weather monitoring equipment, check pheromone traps, and calculate degree days, multiplied by labor cost (\$6.00/hr).

III. The cost of weather monitoring equipment per year was equal to the equipment purchase price, multiplied by the amortization factor (15 %), plus the yearly cost for repair and maintenance.

IV. Trap cost was equal to the number of traps (one trap per 0.8 hectare), multiplied by the purchase price per trap.

V. Chemical cost was equal to the amount of product used multiplied by price per unit.

Control cost for each pest was the sum of the five components listed above. Cost of control was determined for each pest separately. When insecticides and fungicides were mixed and applied in one trip, it was considered two separate trips, one for applying fungicides and the other one for applying insecticides. For additional details on methods used in the economic analysis, see Appendix.

RESULTS

Spray Applications

In 1989, Predictor and LWR treatments, the weather-based spray strategies, received three and four fewer fungicide sprays, respectively, than the traditional treatment (Table 1). In 1990, CR-10 and LWR treatments each received four fewer fungicide sprays than the traditional treatment. The "4-spray" treatment received three and four fewer fungicide sprays for apple scab than the traditional treatment in 1989 and 1990, respectively. The fourth apple scab spray was mistakenly not applied on the "4-spray" treatment in 1990.

Predictor and LWR treatments received five fewer insecticide sprays for codling moth than the traditional treatment in 1989. In 1990, CR-10 and LWR treatments received two fewer insecticide sprays than the traditional treatment. The "4-spray" and "no fungicides" Treatments each received four fewer sprays than the traditional treatment in 1989 and two fewer sprays in 1990. No insecticides were applied for apple maggot in either season.

Overall, for codling moth and apple scab, Predictor/CR-10 and LWR treatments saved eight (Predictor) and nine (LWR) pesticide sprays in 1989, and six pesticide sprays each in 1990, in comparison to the traditional treatment. The "4-spray" treatment saved seven and six pesticide applications in 1989 and 1990, respectively, in comparison to the traditional treatment.

Pests

Apple scab

In 1989, apple scab symptoms were not detected on leaves or fruit. Unusually wet weather during May-July (20) contributed to the appearance of scab in 1990. Foliar symptoms of scab were not detected until mid-August. Incidence in the "no fungicides" treatment was significantly higher than in any other treatment (Table 2). The severity of foliar scab on trees in the "4-spray" treatment was much less than in the "no fungicides" treatment, but significantly higher than in CR-10, LWR treatment. Correspondingly, the "no fungicides" treatment had a greater incidence of scab symptoms on harvested fruit than the other treatments. Scab incidence on dropped fruit was very low.

Codling moth and apple maggot

No apple maggot flies were captured in 1989 or 1990. No apple maggot injury to fruit was found in either year.

Codling moths were captured in pheromone traps in both years (Figures 1 and 2). Codling moth injury to harvested and dropped fruit was found in 1989 (Table 3). The incidence of damage to harvested fruit was not significantly different among treatments, but codling moth incidence in dropped fruit was significantly greater in the "no fungicides" treatment than the CR-10 and "4-spray" treatments. No codling moth injury was detected in 1990.

Yield

In 1989, total yield in the traditional treatment was significantly greater than total yield in the "4-spray" treatment, but marketable, and cull yield were not significantly different among treatments (Tables 4 and 6), but there were significant differences among replications. In 1990, total, marketable, and cull yield and the number of drops (Tables 4 and 5) were much higher than in 1989. The "no fungicides" treatment had a lower yield than any other treatment in 1990. No significant differences in yield existed among CR-10, LWR, traditional and "4-spray" treatments. In Both years, more than 90 % of fruit injury in all treatments was non-pest related injury (mostly mechanical injury) (Table 7). The pest injury was relatively low because of low pressure of pests during both years.

Economic Analysis

Revenue, direct cost and return in both years projected for orchard sizes of 2, 4, 8 and 16 hectares are presented in the Appendix (Tables A3 to A14). Summaries of economic analysis results are presented in Figures 3 to 8.

Direct costs calculated for each treatment except the Predictor/CR-10 treatment increased from 1989 to 1990 as orchard size increased (Fig.'s 3 and 4 and Appendix, Tables A3 to A10). For treatments not utilizing weather-monitoring equipment (traditional, "4-spray" and "no fungicides" treatments), costs in each year rose in proportion to orchard size. In other words, as orchard size doubled, costs for these treatments doubled (Fig.'s 3, 4 and 5). However, in treatments utilizing weather-monitoring

equipment, costs rose more slowly than orchard size increased (Fig.'s 3 and 4). For example, for the Predictor treatment in 1989, as orchard size doubled (from 2 to 4, 4 to 8 and 8 to 16 hectares), costs increased by 41 to 78 % (Appendix, Tables A3 to A14).

In all cases (1989, 1990 and (1989 + 1990)), revenues increased proportionally as orchard size increased (Appendix, Tables A3 to A14). In 1989 and 1990, return (revenue minus cost) was largest in the traditional treatment (Fig. 6) and the CR-10 treatment (Fig. 7), respectively. For both years combined, return was highest in the Predictor/CR-10 treatment (Fig. 8). Revenue had a larger influence than cost on year-to-year differences in return. In 1989, there were no significant differences in return among treatments (Appendix, Tables A3 to A6) (LSD, $P = 0.05$). In 1990, returns for the CR-10 treatment were significantly greater than for all other treatments at all orchard sizes (Appendix, Tables A7 to A10). LWR, traditional and "4-spray" treatments were not significantly different from each other, and the "no fungicides" treatment had significantly smaller returns than all other treatments.

For combined (1989 + 1990) returns (Fig. 8), there were no significant differences among treatments at 2- or 4-hectare orchard sizes. However, for 8- and 16-hectare orchard sizes, return for the Predictor/CR-10 treatment was significantly greater, and return for "no fungicides" treatment was significantly less than for other treatments.

DISCUSSION

The present study looked simultaneously at codling moth, apple maggot and apple scab. Earlier studies in the Upper Midwest (26, 71) focused on either insects or diseases rather than both types of pest. Therefore, the present study attempted to comprehend a greater proportion of orchardists' pest problems and IPM management needs in this region than these earlier studies. A comprehensive IPM field study has been conducted in other regions (95).

Spray Applications and Pest Control

Utilization of IPM-based spray programs resulted in a substantial reduction in the number of pesticide applications for apple scab and codling moth in comparison to traditional grower practice in both years (Table 1). Despite substantial spray savings in the IPM-based treatments, control of scab and codling moth was equivalent to control by the traditional spray schedule. Yield and quality of fruit were greater than or comparable to the traditional treatment. This is comparable to the findings of Funt et al. (26), who saved an average of 3.7 sprays for apple scab control per year in their 7-year study in Ohio. Similarly, the level of scab control they obtained on apples from the weather-based treatments was equivalent to that on apples from the "traditional" spray treatment.

For both years combined, the level of pest control obtained by IPM-based programs (Predictor/CR-10, LWR and "4-spray" treatments) was equivalent to that of the "traditional" spray program. Moreover, these

IPM-based programs led to reducing the number of pesticide applications for these two pests by an average of 44 percent during 1989-90 in comparison to the "traditional" spray program.

Apple scab symptoms did not develop on leaves or fruit in 1989. The extremely dry weather conditions in 1988 (18) probably produced little inoculum for 1989 (3, 76). Continued drought in 1989 (19) resulted in the absence of apple scab lesions on foliage and fruit. Therefore, no conclusions could be drawn about the ability of any treatments to control apple scab in the IPM-based treatments in 1989.

Unusually wet weather conditions in 1990 (20), as well as the introduction of inoculum, may have contributed to the development of apple scab symptoms on fruit and foliage late in the growing season. The absence of foliar symptoms of scab in spring 1990 suggested that there was no primary infection from ascospores. This may have been due to a low level of overwintering inoculum, despite incorporation of infected leaves in the test plot in December 1989. Symptom development during August through October of 1990 was probably caused by conidia produced on trees outside the orchard during the summer. This is consistent with Hirst and Stedman's (48) conclusion that conidia are important in establishing the disease in orchards that previously had been scab-free.

The absence of apple maggot flies in either year, and of apple maggot injury to fruit, indicated that apple maggot was not a serious insect pest at the Horticulture Station in 1989 or 1990. This is in agreement with the finding of Freiburger (24), who reported capturing only

one apple maggot adult at Horticulture Station during a study that spanned from spring of 1978 to summer of 1980.

Yields

The relatively higher yields in 1990 were probably due to effects of tree age, as they increased their bearing surface, and to much higher rainfall in 1990 (20).

Economic Analysis

Direct costs calculated for each treatment differed from 1989 to 1990 (Fig.'s 3 and 5) due to changes in number of pesticide sprays, changes in equipment and methods (Predictor/CR-10 treatment), and changes in pesticides used (see Appendix). Direct costs for weather-based treatments (Predictor/CR-10 and LWR treatments) rose more slowly with increasing orchard size than for any other treatment. The relatively low rate of increase in costs for weather-based treatments was because, in flat open terrain, a single weather monitor (Predictor, Leaf Wetness Recorder or CR-10) was sufficient for an area of up to 16 hectares (40 acres). Therefore, monitoring costs per hectare fell as orchard size increased. This confirms the finding of Funt et al. (26) that the efficiency of monitoring equipment increased as orchard size increased. In contrast, direct costs per hectare for traditional, "4-spray" and "no fungicides" treatments rose in direct proportion to increasing orchard size. As a result, larger orchards up to 16 hectares realize increasing economies of scale for weather monitoring.

Based on combined cost from both years (Fig. 5 and Appendix Tables A11 to A14), orchard size at which costs of Predictor/CR-10 treatment equal costs of the traditional treatment was between 8 and 16 hectares, whereas orchard size at which costs of the LWR treatment equal that of the traditional treatment was between 2 and 4 hectares. The use of expensive monitoring equipment in the Predictor treatment in 1989 made this treatment more cost-effective compared to the traditional treatment only at larger orchard sizes (8 to 16 hectares), while the use of relatively cheaper monitoring equipment in the LWR treatment in 1989 made this treatment more cost-effective starting at smaller orchard sizes (2 to 4 hectares). However, use of cheaper monitoring equipment in the CR-10 treatment during 1990, left the LWR treatment as the most expensive treatment at all orchard sizes except 16 hectares, where the traditional treatment was more expensive. Thus changes between study years in equipment used in treatment 1 (Predictor/CR-10) complicated comparison of this treatment to the other treatments on the basis of both years combined.

The "4-spray" treatment was more cost-effective than Predictor/CR-10, LWR or the traditional treatments 1, 2 or 3 at all orchard sizes. This was because of the fact that no disease-monitoring equipment was used in this treatment. The "no fungicides" treatment was the least expensive treatment at all orchard sizes.

In each year and in both years combined, return was calculated using this formula: $\text{return} = \text{revenue} - \text{direct costs}$. Revenue is a reflection of yield, which is, in turn, a factor of variety, rootstock,

treatment, soil, weather, and other factors. Direct costs are a reflection of methodology. Therefore, one can conclude that return reflects both yield and methodology. Due to the heterogeneity in rootstocks and the variability in tree size, interpretation of the return results are more equivocal than interpretation of the cost results.

SUMMARY AND CONCLUSIONS

From this two-year study, it was concluded that:

1. The IPM-based spray strategies saved an average of seven pesticide sprays (8 in 1989 and 6 in 1990) for control of two major apple pests, apple scab and codling moth, compared to a "traditional" spray schedule that is currently used by commercial apple growers in Iowa.

2. Pest control efficacy, yield, and fruit quality in IPM-based treatments were comparable to or greater than the traditional treatment.

3. Cost of weather-based treatments declined relative to cost of the traditional treatment as orchard size increased from 2 to 16 hectares.

4. The IPM treatment that used the least expensive monitoring equipment ("4-spray" treatment) was the most cost-effective treatment at all orchard sizes.

5. The IPM-based treatments resulted in returns comparable to or greater than those of a "traditional" spray schedule.

In conclusion, applying pesticides only when weather and pest populations pose risk of pest outbreaks resulted in substantial savings in money and time. Fewer pesticide sprays may have reduced environmental pollution as well, but this factor was not quantified in the present study. If these findings are sustained by additional research, and adopted by commercial apple growers in Iowa, IPM-based spray programs will provide growers with spray strategies that will substantially reduce cost and time, increase profitability and possibly reduce environmental contamination.

Table 1. Total number of pesticide sprays for primary apple scab ("scab") and codling moth ("moth") in 1989 and 1990

Treatment	1989		1990		Total sprays ^a	
	scab	moth	scab	moth	1989	1990
1) Predictor or CR-10	4	4	3	7	8	10
2) Leaf Wetness Recorder	3	4	3	7	7	10
3) "traditional" schedule	7	9	7	9	16	16
4) "4-spray"	4	5	3	7	9	10
5) no fungicides	0	5	0	7	5	7

^aFor control of apple scab and codling moth only

Table 2. Apple scab incidence and severity on leaves and incidence on fruit in 1990

Treatment	Incidence ^a (leaves)	Severity ^b (leaves)	Incidence ^c on harvested fruit	Incidence ^c on dropped fruit prior to harvest
1) CR-10	0.34	0.34	0.00	0.31
2) Leaf Wetness Recorder	0.93	1.10	0.11	0.00
3) "traditional" schedule	0.84	0.61	0.00	0.00
4) "4-spray"	2.97	2.20	0.00	0.00
5) no fungicides	21.98	12.28	2.18	0.73
LSD, P = 0.05	3.65	1.64	1.13	0.56

^aApple scab incidence on leaves is the average percent of leaves showing scab symptoms.

^bApple scab severity on leaves is the average number of scab lesions per symptomatic leaf.

^cApple scab incidence on fruit is the average percent of fruit with scab lesions.

Table 3. Codling moth injury to harvested and dropped fruit (fruit that had dropped prior to harvest) in 1989

Treatment	incidence in harvested fruit ^a	incidence in dropped fruit ^a
1) Predictor	0.09	0.45
2) Leaf Wetness Recorder	0.13	1.71
3) "traditional" schedule	0.00	2.46
4) "4-spray"	0.00	0.45
5) no fungicides	0.34	5.25
LSD, P = 0.05	0.48	3.78

^aCodling moth incidence in fruit is the mean percent of fruit with codling moth injury.

Table 4. Total yield (kg per hectare) in 1989, 1990 and (1989 + 1990)

Treatment	1989	1990	(1989 + 1990)
1) Predictor or CR-10	6044.47	11840.19	17884.66
2) Leaf Wetness Recorder	6146.91	10214.82	16361.73
3) "traditional" schedule	6724.33	11056.77	17781.10
4) "4-spray"	4632.97	10209.19	14842.16
5) no fungicides	5284.70	6615.16	11899.86
LSD, P = 0.05	1751.30	2193.19	-

Table 5. Number of fruit that had dropped per 0.4 hectare (acre) prior to harvest in 1989, 1990 and (1989 + 1990)^a

Treatment	1989	1990	(1989 + 1990)
1) Predictor or CR-10	1678.00	3367.00	5045.00
2) Leaf Wetness Recorder	1467.00	5196.00	6663.00
3) "traditional" schedule	1809.00	2985.00	4794.00
4) "4-spray"	2040.00	4181.00	6221.00
5) no fungicides	1688.00	4382.00	6070.00
LSD, P = 0.05	694.55	1066.59	—

^aDropped fruit were counted at harvest

Table 6. Yield categories in percent: Culls (fruit with any blemishes, e.g. insect entries, diseased spots, mechanical injury, etc.) and good (blemish-free fruit)

Treatment	1989				1990			
	Culls		Good		Culls		Good	
	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%
1) Predictor or CR-10	2999.27	49.62	3045.20	50.38	6053.89	51.13	5786.30	48.87
2) Leaf Wetness Recorder	3234.50	52.62	2912.41	47.38	5305.58	51.94	4909.24	48.06
3) "traditional" schedule	3711.83	55.20	2012.50	44.80	6730.26	60.87	4326.51	39.13
4) "4-spray"	2326.21	50.21	2306.76	49.79	5631.39	55.16	4577.80	44.84
5) no fungicides	2846.34	53.86	2438.36	46.14	4052.44	61.26	2562.71	38.74
LSD, P = 0.05	-	8.69	-	8.69	-	5.50	-	5.50

Table 7. Cause of injury to culled apples (numbers are in percent)

Treatment	1989			1990		
	codling moth	other pests ^a	non-pest related injury	apple scab	other pests ^a	non-pest related injury
1) Predictor or CR-10	0.09	3.53	96.36	0.0	3.29	96.71
2) Leaf Wetness Recorder	0.13	5.02	94.44	0.20	2.06	97.74
3) "traditional" schedule	0.0	5.56	94.44	0.0	3.64	96.36
4) "4-spray"	0.0	4.48	95.51	0.0	2.55	97.45
5) no fungicides	1.89	0.34	97.76	3.13	5.52	91.35
LSD, P = 0.05	0.48	3.70	3.67	1.13	2.85	3.00

^aOther pests include insects in hymenoptera family and other unidentified insects.

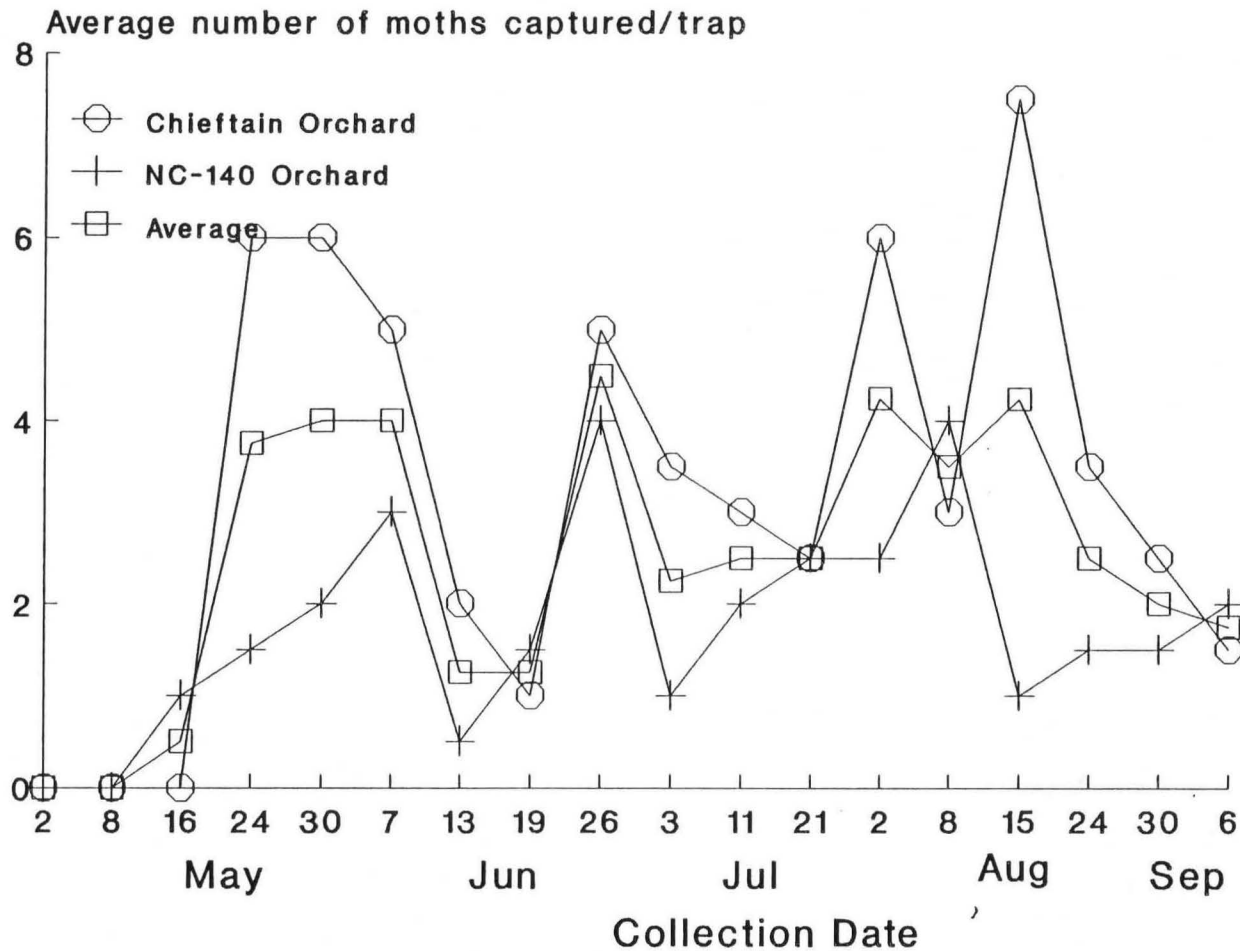


Figure 1. Flight activity of codling moth, *Laspeyresia pomonella*, as determined by weekly captures in pheromone traps at Horticulture Station during 1989. The experiment was conducted in the NC-140 orchard, but the average trap captures in the NC-140 and a nearby (about 0.2 km) block of Chieftain was used to help determine timing of insecticide sprays in this study.

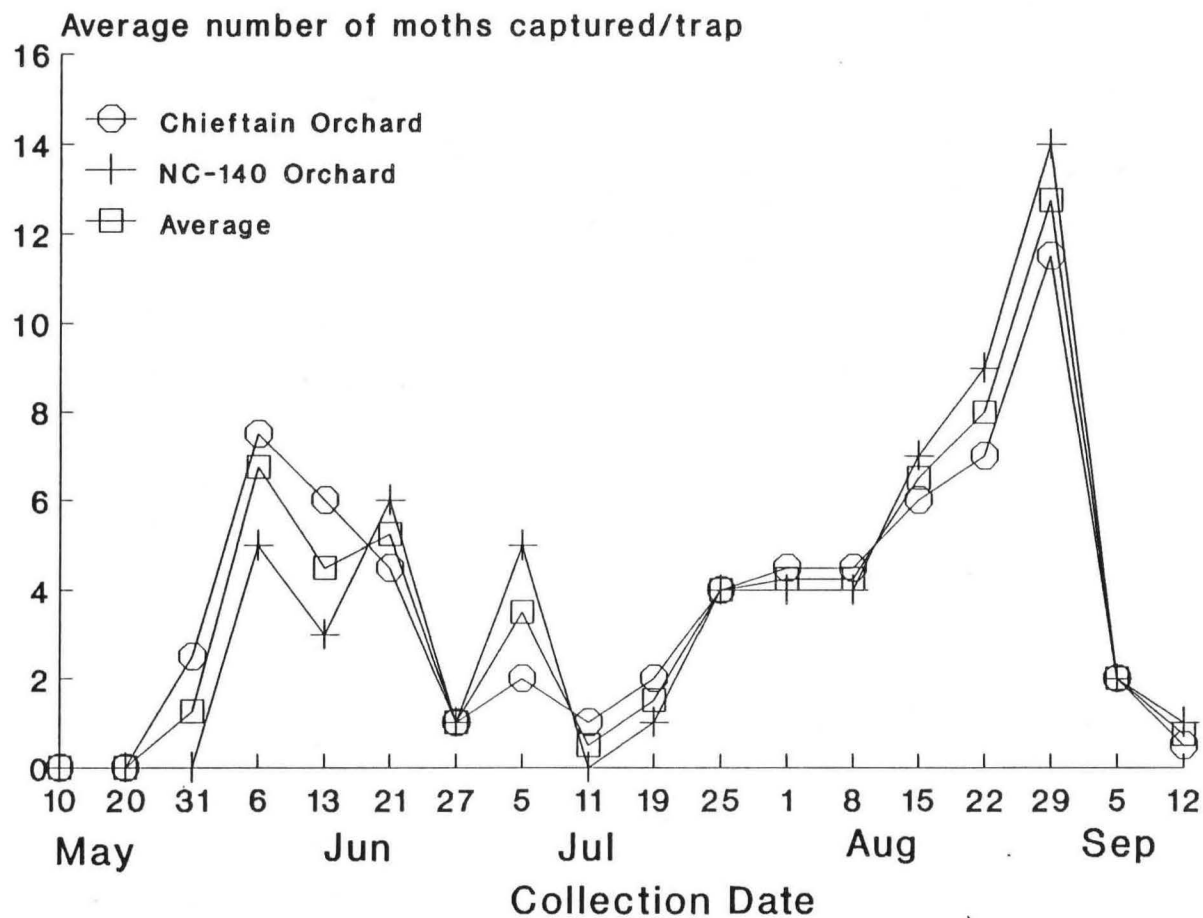


Figure 2. Flight activity of codling moth, *Laspeyresia pomonella*, as determined by weekly captures in pheromone traps at Horticulture Station during 1990. The experiment was conducted in the NC-140 orchard, but the average trap captures in the NC-140 and a nearby (about 0.2 km) block of chieftain was used to help determine timing of insecticide sprays in this study.

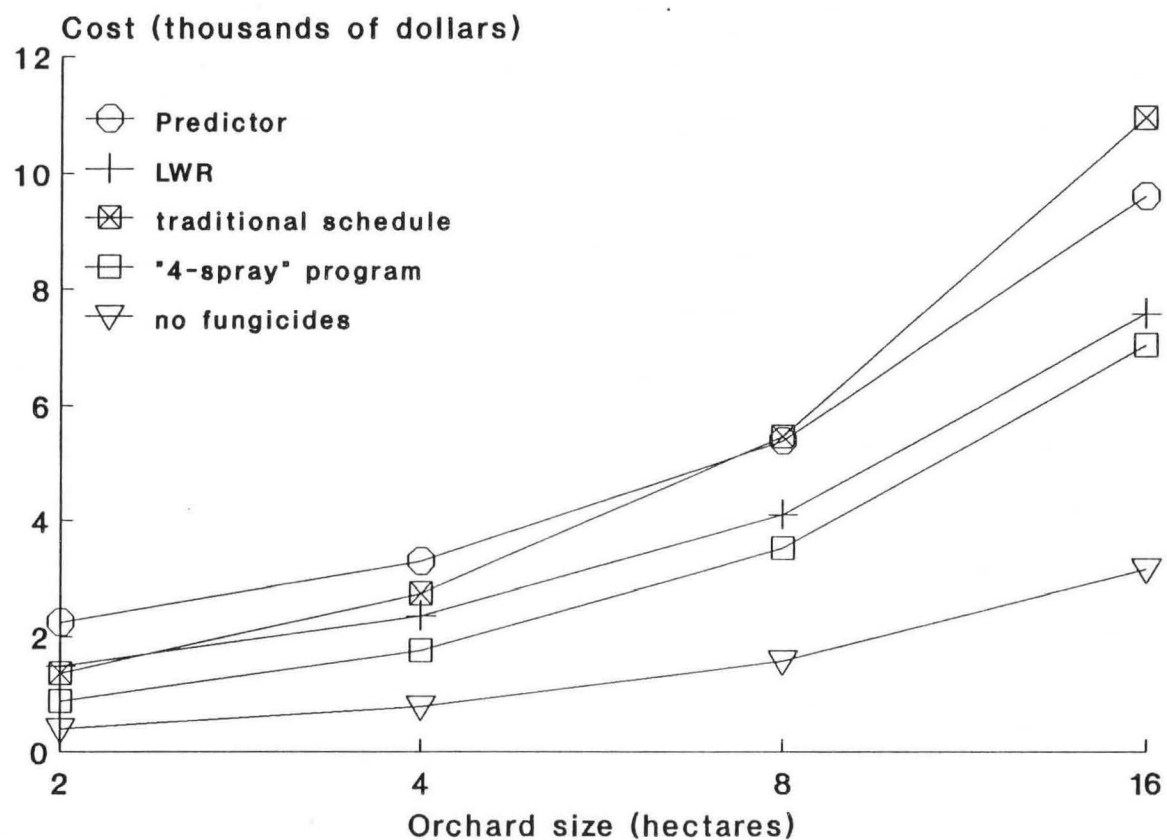


Figure 3. Direct cost to control apple scab and codling moth in 1989 for orchard sizes of 2, 4, 8 and 16 hectares.

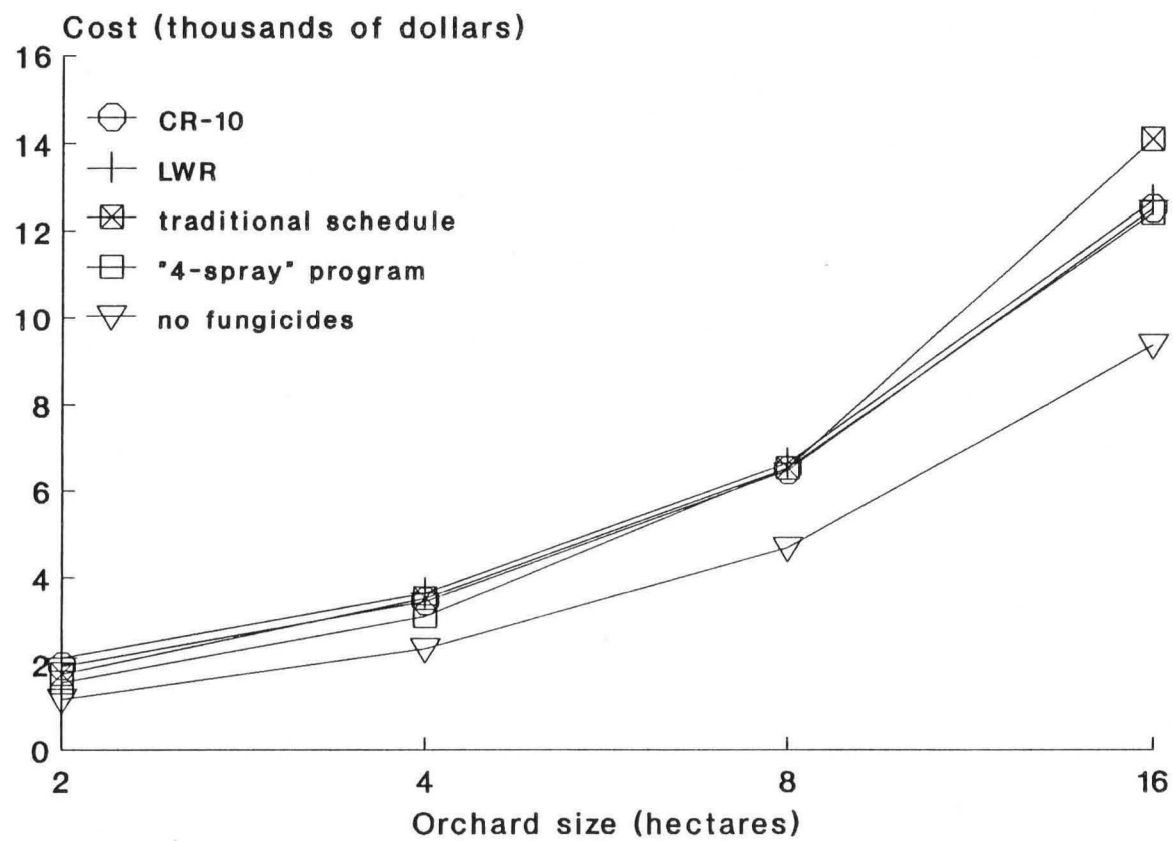


Figure 4. Direct cost to control apple scab and codling moth in,1990 for orchard sizes of 2, 4, 8 and 16 hectares.

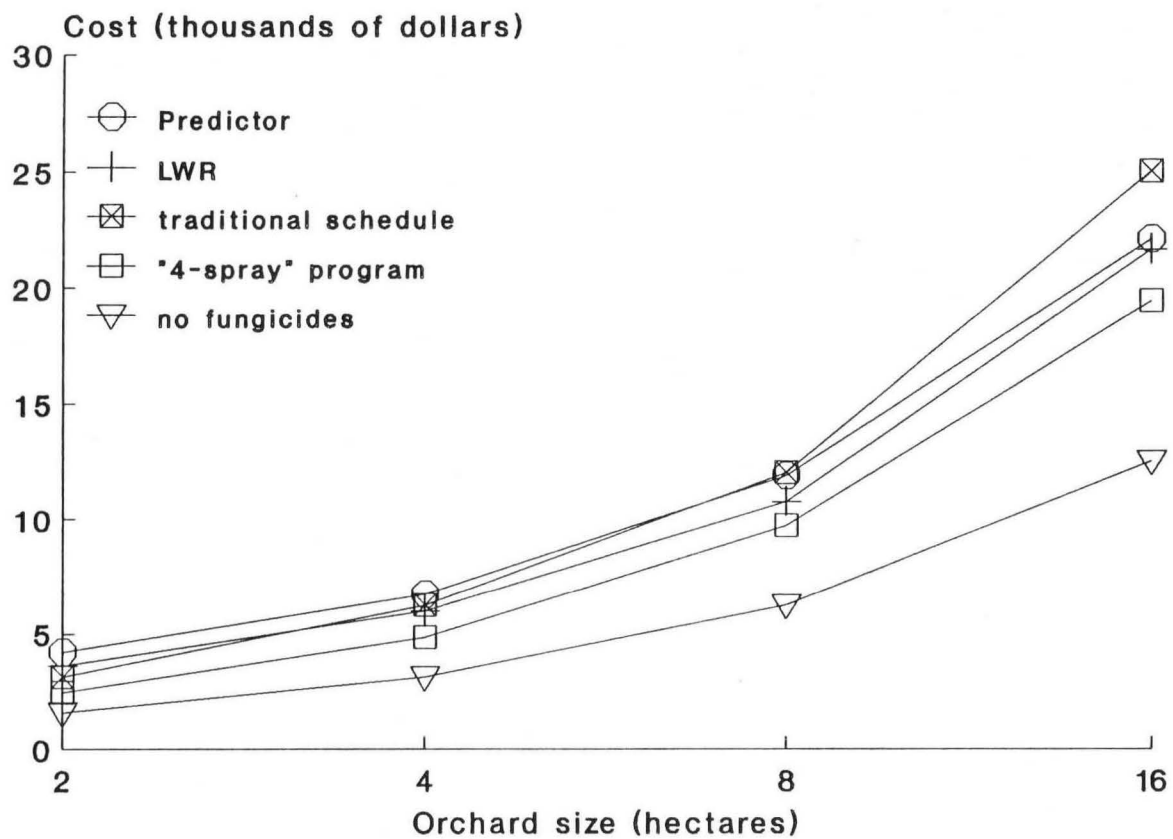


Figure 5. Direct cost to control apple scab and codling moth in,(1989 +1990) for orchard sizes of 2, 4, 8 and 16 hectares.

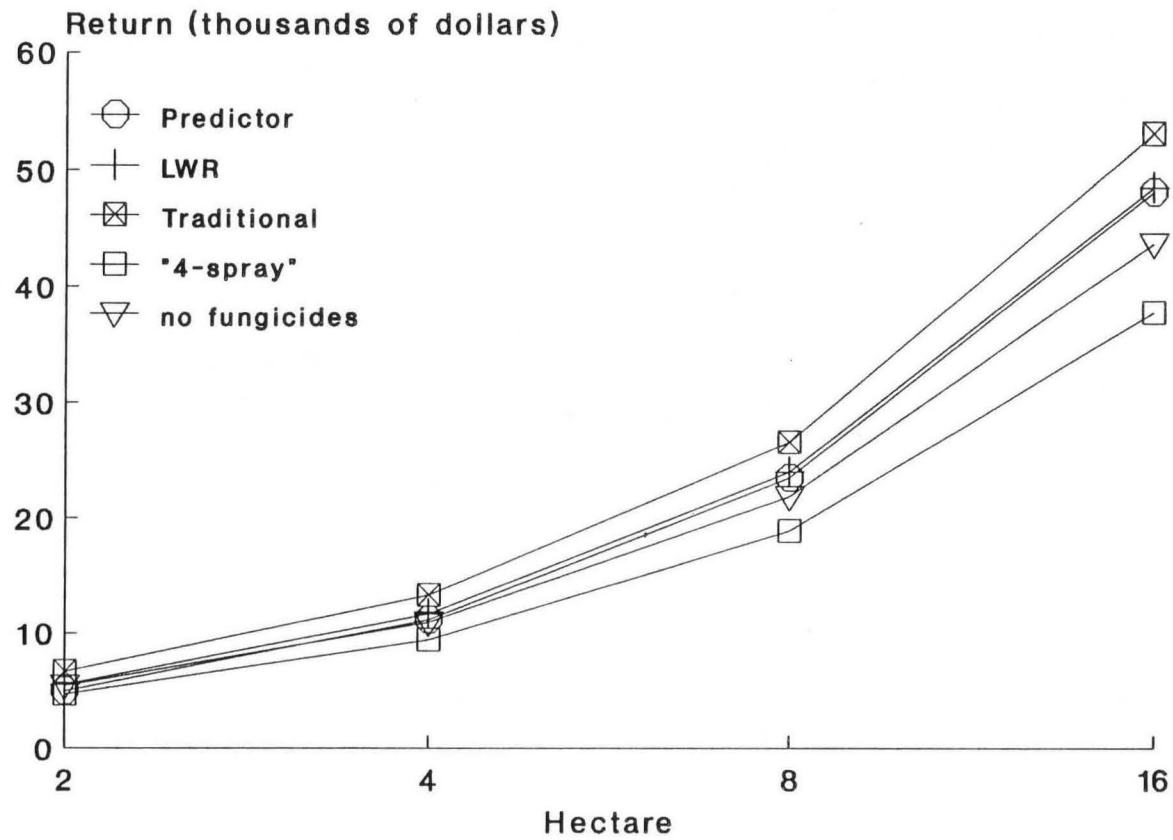


Figure 6. Return (revenue minus cost of apple scab and codling moth control) from 1989 for orchard sizes of 2, 4, 8 and 16 hectares.

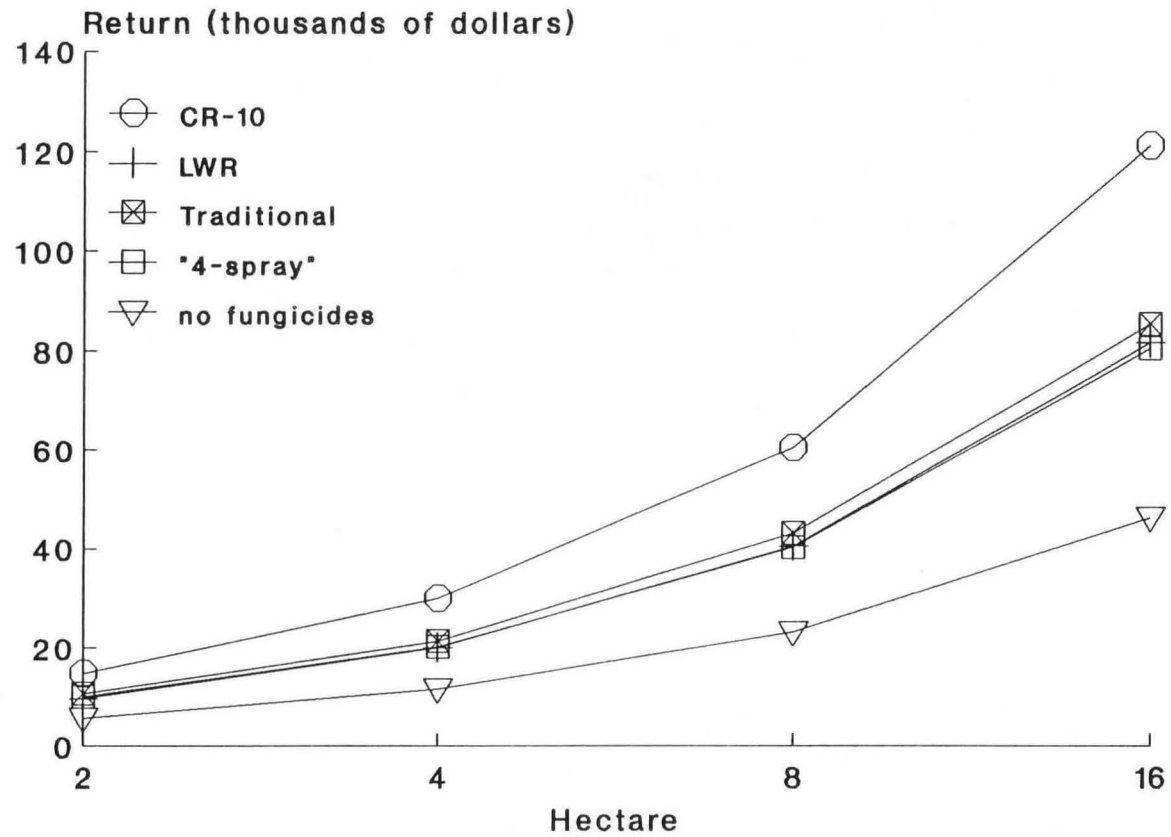


Figure 7. Return (revenue minus cost of apple scab and codling moth control) from 1990 for orchard sizes of 2, 4, 8 and 16 hectares.

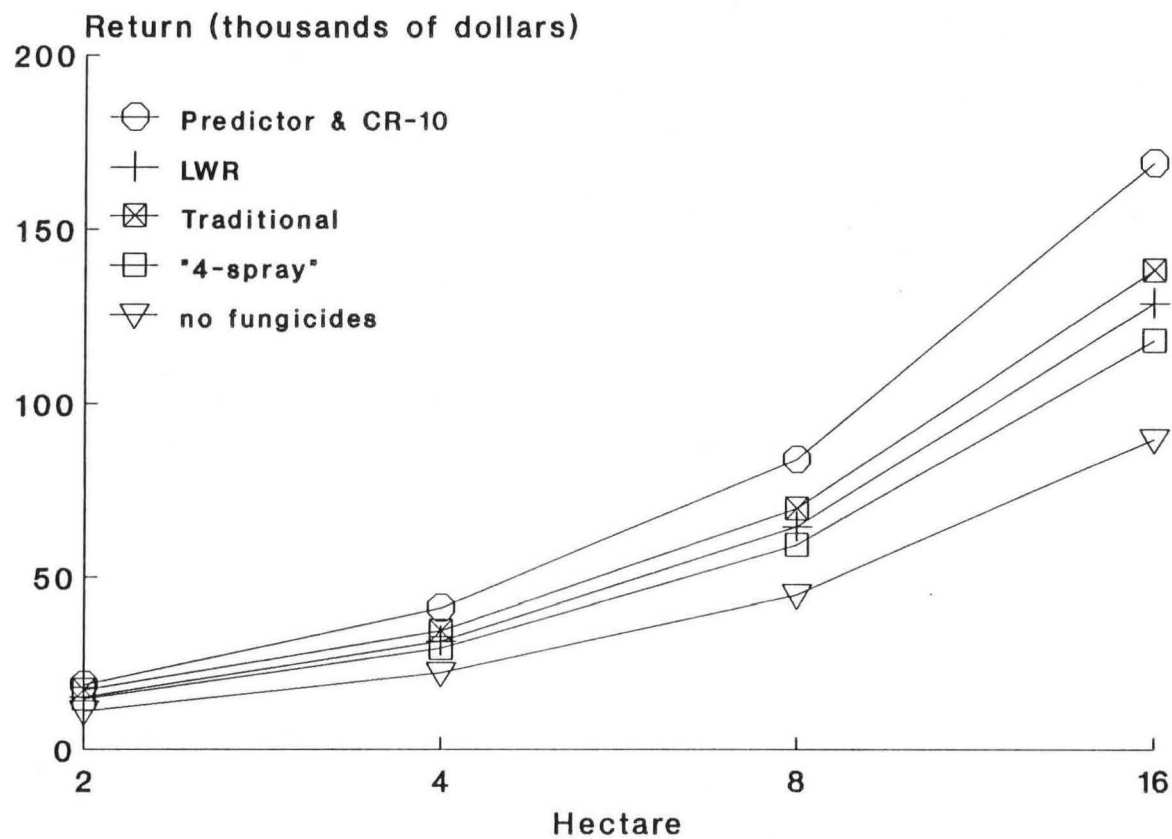


Figure 8. Return (revenue minus cost of apple scab and codling moth control) from (1989 + 1990) for orchard sizes of 2, 4, 8 and 16 hectares. ,

INTRODUCTION

Ascospores, the sexual spores of the fungus Venturia inaequalis, are the major source of primary infection in an apple scab epidemic (3, 29, 30, 111). They are released from overwintered, infected apple leaves during rainfall periods (3), land on apple leaves, and can germinate and induce infection when the leaves are coated with a film of free water (10, 13).

A key unanswered question concerns the factors that affect survival and activity of spores on leaves before infection occurs (80). The duration of ascospore survival on a dry leaf surface is unknown. Although some researchers have assumed that ascospores can infect leaves in the absence of water films when relative humidity exceeds 90 % (7), there is no direct evidence to support this assumption.

The objective of the preliminary experiments performed here was to clarify the effects of relative humidity on survival of ascospores of Venturia inaequalis in the absence of free water.

MATERIALS AND METHODS

Ascospore Trapping in Laboratory and Relative Humidity Experiments

In order to study ascospore viability after release, it was first necessary to capture ascospores in a nondestructive manner.

Several types of traps have been designed to catch ascospores and other fungal spores. A laboratory-tested trap is the "spore tower" (H. Shaffer, Department of Plant Pathology, University of Missouri, personal communication). The spore tower is a plexiglas rectangle 60 cm tall x 20 cm wide x 20 cm deep. The structure is capped with a wire basket containing a 3 cm layer of loosely packed leaves. Air is drawn through the leaves to the bottom of the tower by a vacuum pump. A screen platform holding 10 microscope slides is inserted into the chamber immediately above the air outlet. Spores released from the leaves impact on the slides.

Apple leaves and ascospore capture

Scab-infected apple leaves were obtained from an orchard near New Franklin, Missouri in April, 1990, and stored at room temperature (approximately 20 C). In April-June, 1990, the degree of maturation of ascospores was assessed by microscopic examination of crushed perithecia according to criteria of Szkolink (111), in order to determine their readiness to be released. Using these criteria, perithecia were rated on a maturity scale from 1 to 4 as follows: 1) perithecia with asci formed and spores in process of formation; 2) full size, usually septate but not

colored, spores are formed; 3) mature ascospores are formed (maturity was indicated by pale green-yellow color for septate spore, two-celled spores); and 4) ascospores are ejected from asci (indicated by empty asci).

Ascospores for use in experiments were captured by air-drying overwintered, scab-infected leaves displaying mature perithecia. To induce ascospore release, the leaves were soaked in water for 30 seconds (110), drained of excess water, placed in sealed crispers for 24 hours at room temperature (20 C), and air-dried. After two wetting and drying periods of 24 hr each, a subsample of dry leaves was moistened and placed in a spore tower. Ten microscope slides (precoated with plastic, double-sided adhesive tape) were placed on the screen platform, and air was drawn through wet leaves by a vacuum pump for 2 hours. Three spore towers were used in order to obtain sufficient ascospores for the relative humidity trials described below.

Microscope slides on which at least 10 ascospores were captured were placed in moist chambers and transferred immediately to racks in controlled-humidity chambers. Using glycerol solutions of specified concentrations, the chambers were adjusted to maintain relative humidities of 30 %, 60 %, or 90 % at 20 C for about one week before the beginning of the experiment (Denis McGee, Department of Plant Pathology, Iowa State University, personal communication). Equilibration to the desired relative humidity level was verified by hygrothermographs (Cole-Parmer, Inc, Chicago, Illinois) before and after each experiment. Nine slides were placed in each relative humidity chamber. Relative humidity chambers

were placed in fluorescent light at 20 C in a temperature-controlled incubator at the Seed Science Building, Iowa State University, Ames, IA. At intervals of 6, 24 and 72 hours (experiment 1) or 6, 24 and 48 hours (experiments 2 and 3), 3 slides were removed from each chamber and placed in a 100 % relative humidity (RH) chamber. The 100 % RH chamber was a dew chamber in experiment 1 and plastic crispers with wet paper towels in experiments 2 and 3. After 24 and 48 hours, slides were removed and examined under a compound microscope. The total number of ascospores per slide, the percent of spores that had germinated (produced germ tubes), and mean germ tube length were determined.

RESULTS AND DISCUSSION

Release of mature ascospores from perithecia was induced by repeated wetting and drying intervals. Mature ascospores of Venturia inaequalis as well as ascospores and asexual spores of other fungi were caught on slides in the spore tower. The change in ascospore color from clear to pale green-yellow, repeatedly associated with maturation (110), was not observed.

Ascospore germination in response to relative humidity treatments varied widely among the three trials. A 48-hr exposure to 90 % relative humidity resulted in higher ascospore germination than exposure to 30 or 60 % relative humidity for the same period (Tables 8, 9 and 10). However, effects of the length of exposure time within each humidity treatment were inconsistent among the trials. In contrast, high relative humidity was found to reduce survival of conidia (the asexual spores of apple scab fungus) at the same temperature, 20 C (47).

Several factors may have contributed to variability among the trials:

1. Methodological variation among trials. For example, in trial 1, slides were covered with a film of free water after treatment in dew chamber. This may have led to loss of ascospores by washing off. In trials 2 and 3, free water films did not form on the surface of slides, so washoff did not occur.
2. Ascospore viability may not have been consistent among trials.

3. The double-stick tape may have affected spore viability.
4. Presence of spores of other fungi sometimes made it difficult to distinguish ascospores of V. inaequalis from those of other fungi.

Because of variability and inconsistency of results in these preliminary trials, conclusions about the effect of the relative humidity on ascospore viability cannot be drawn.

SUMMARY

We successfully demonstrated a convenient method to capture viable ascospores of V. inaequalis for use in controlled experiments.

Methodological improvements should improve consistency of results in future studies of relative humidity effects on ascospore viability.

Table 8. Experiment 1. Percent of ascospores germinated under different combinations of relative humidities (RH) at temperature of 20 C in light

Relative Humidity in the Chamber								
30 %			60 %			90 %		
Hours at this RH	Hours in dew chamber (RH = 100%)	Germination (%)	Hours at this RH	Hours in dew chamber (RH = 100%)	Germination (%)	Hours at this RH	Hours in dew chamber (RH = 100%)	Germination (%)
6	24	0.0	6	24	28	6	24	9.09
	48	23.08		48	20.83		48	60
24	24	11.11	24	24	17.39	24	24	29.41
	48	12.55		48	37.50		48	41.67
72	24	2.63	72	24	20	72	24	0.0
	48	8.30		48	16.23		48	14.68

Table 9. Experiment 2. Percent of ascospore germinated under different combinations of relative humidities (RH) at temperature of 20 C and light

Relative Humidity in the Chamber								
30 %			60 %			90 %		
Hours at this RH	Hours in crisper (RH = 100%)	Germination (%)	Hours at this RH	Hours in crisper (RH = 100%)	Germination (%)	Hours at this RH	Hours in crisper (RH = 100%)	Germination (%)
6	24	0.0	6	24	0.0	6	24	16.81
	48	8.16		48	14.28		48	8.57
24	24	0.0	24	24	0.0	24	24	13.73
	48	18.37		48	27.27		48	41.27
48	24	5.88	48	24	15.38	48	24	23.33
	48	13.33		48	16.67		48	46

Table 10. Experiment 3. Percent of ascospore germinated under different combinations of relative humidities (RH) at temperature of 20 C and light

Relative Humidity in the Chamber								
30 %			60 %			90 %		
Hours at this RH	Hours in crisper (RH = 100%)	Germination (%)	Hours at this RH	Hours in crisper (RH = 100%)	Germination (%)	Hours at this RH	Hours in crisper (RH = 100%)	Germination (%)
6	24	4.71	6	24	11.43	6	24	14.29
	48	23.8		48	16.81		48	7.14
24	24	8	24	24	11.76	24	24	44.18
	48	18.18		48	20		48	50
48	24	33.33	48	24	30	48	24	13.46
	48	44.44		48	37.50		48	15.38

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PART II. INFLUENCE OF RELATIVE HUMIDITY ON THE SURVIVAL OF
ASCOSPORES OF THE FUNGUS VENTURIA INAEQUALIS

APPENDIX

The data included in this appendix are portions of the data belonging to part I.

Table A1. Plan for spray timing and pesticides used, field experiment, 1989. All rates are per 95 liters (25 gallons) diluted spray unless otherwise noted. Table A1 continues on

Timing (developmental stage)	Treatment				
	1	2	3	4	5
green tip	post-infection (Predictor) (see footnote) 1 % dormant oil	post-infection (Leaf Wetness Recorder) (see footnote) 1 % dormant oil	Benlate 0.5 oz + Dithane M45 3 oz 1 % dormant oil	none	1 % dormant oil
tight cluster	post-infection	post-infection	Benlate 0.5 oz + Dithane M45 3 oz	Nova 0.5 oz 1 % dormant oil	none
pink	post-infection Thiodan 4 oz	post-infection Thiodan 4 oz	Benlate 0.5 oz + Dithane M45 3 oz Thiodan 4 oz	Nova 0.31 oz + Dithane F45 0.4 qt Thiodan 4 oz	Thiodan 4 oz
bloom	post-infection	post-infection	Benlate 0.5 oz + Dithane M45 3 oz	none	none
petal fall	post-infection Imidan 4 oz	post-infection Imidan 4 oz	Benlate 0.5 oz + Dithane M45 3 oz Imidan 4 oz	Nova 0.31 oz Imidan 4 oz	Imidan 4 oz

first cover	post-infection degree-day criteria + trap captures*	post infection degree-day criteria + trap captures *	Dikar 8 oz Imidan 4 oz	Nova 0.31 oz + Dithane F45 0.2 qt	as determined by trap captures**
second cover (7-10 days after first cover)	post-infection degree-day criteria + trap captures*	post-infection degree-day criteria + trap captures*	Dikar 6 oz Imidan 4 oz	Dikar 8 oz as determined by trap captures**	as determined by trap captures**
third cover until three weeks before harvest (10- 14 days between sprays)	Dikar 6 oz degree-day criteria + trap captures**	Dikar 6 oz degree-day criteria + trap captures**	Dikar 6 oz Imidan 4 oz	Dikar 6 oz as determined by trap captures**	as determined by trap captures**
three weeks before harvest until harvest (10- 14 days between sprays)	Captan 4 oz degree-day criteria + trap captures*	Captan 4 oz degree-day criteria + trap captures*	Captan 4 oz Imidan 4 oz (until 1 week before harvest)	Captan 4 oz as determined by trap captures**	as determined by trap captures**

Note: All post-infection fungicide sprays should be as follows: Nova 0.5 oz + Dithane F45 0.2 qt/25 gallons dilute spray.

*For this treatment, spray Imidan (4 oz/25 gallons) only when both of the following criteria are met:

1. Threshold capture per trap (codling moth: an average of at least 2 adults per trap; apple maggot: any adults caught in any trap).
2. degree-day thresholds: 550 and 1550 degree-days (base = 50 F) since 1 March for the second and third generations of codling moth, respectively. And 1137 degree-days (base = 43 F) since 1 March for the second generation of apple maggot.

**For this treatment, apply Imidan (4 oz/25 gallons) 1 week after average of 2 codling moth captures per trap; apply Imidan (4 oz/25 gallons) 10 to 14 days after any apple maggot adults are trapped.

Table A2. Plan for spray timing and pesticides used, field experiment, 1990. All rates are per 95 liters (25 gallons) diluted spray unless otherwise noted. Table A2 continues on

Timing (developmental stage)	Treatment				
	1	2	3	4	5
green tip	post-infection (CR-10) (see footnote) Superior oil (0.5 gallon)	post-infection (Leaf Wetness Recorder) (see footnote) Superior oil (0.5 gallon)	Benlate 0.75 oz + Captan 4 oz Superior oil (0.5 gallon)	none	Superior oil (0.5 gallons)
tight cluster	post-infection	post-infection	Benlate 0.75 oz + Captan 4 oz	Nova 0.62 oz Superior oil (0.5 gallon)	none
pink	post-infection Thiodan 4 oz	post-infection Thiodan 4 oz	Benlate 0.75 oz + Nova 0.5 oz Thiodan 4 oz	Nova 0.62 oz + Thiodan 4 oz	Thiodan 4 oz
bloom	post-infection	post-infection	Benlate 0.75 oz + Nova 0.5 oz	none	none

petal fall	post-infection Imidan 4 oz	post-infection Imidan 4 oz	Benlate 0.75 oz + Nova 0.5 oz Imidan 4 oz	Nova 0.62 oz Imidan 4 oz	Imidan 4 oz
first cover	post-infection trap captures*	post infection trap captures*	Captan 6 oz Imidan 4 oz	Nova 0.62 oz + trap captures*	trap captures*
second cover (7-10 days after first cover)	post-infection trap captures*	post-infection trap captures*	Captan 6 oz Imidan 4 oz	Captan 6 oz trap captures*	trap captures*
third cover until three weeks before harvest (10- 14 days between sprays)	Captan 6 oz trap captures*	Captan 6 oz trap captures*	Captan 6 oz Imidan 4 oz	Captan 6 oz trap captures*	trap captures*
three weeks before harvest until harvest (10- 14 days between sprays)	Captan 6 oz + Benlate 0.75 oz trap captures*	Captan 6 oz + Benlate 0.75 oz trap captures*	Captan 6 oz + Benlate 0.75 oz trap captures*	Captan 6 oz + Benlate 0.75 oz trap captures*	trap captures*

Note: All post-infection fungicide sprays should be as follows: Nova 0.5 oz + Captan 8 oz (per 25 gallons) dilute spray.

*For this treatment, spray Imidan (4 oz/25 gallons) one week after threshold captures per trap (codling moth: an average of at least 2 adults per trap; apple maggot: any adults caught in any trap) are reached.

Note: Degree-day accumulations should be determined using maximum and minimum air temperature as determined by the Leaf Wetness Recorder (in treatment 2). Degree-day data will be used in making spray decisions after a biofix is established (see part 1, treatments).

Table A3. Revenue, cost and return per season for a 2-hectare (5 acres) orchard size, 1989

treatment	total revenue per 2 hectares	total cost per 2 hectares	total return per 2 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 2 hectares	
					apple scab	codling moth
1) Predictor	7223.70	2249.07	4974.63	994.93	1916.74	332.33
2) Leaf Wetness Recorder	7015.25	1492.83	5522.42	1104.48	1160.50	332.33
3) "traditional" schedule	8006.60	1368.85	6637.75	1327.55	688.80	680.05
4) "4-spray"	5597.35	914.43	4682.92	936.58	484.90	429.53
5) no fungicides	5856.70	429.53	5427.17	1085.43	00.00	429.53
LSD, P = 0.05	-	-	653.39	-	-	-

Table A4. Revenue, cost and return per season for a 2-hectare (5 acres) orchard size, 1990

treatment	total revenue per 2 hectares	total cost per 2 hectares	total return per 2 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 2 hectares	
					apple scab	codling moth
1) CR-10	16714.15	1946.31	14767.84	2953.57	766.38	1179.93
2) Leaf Wetness Recorder	11793.70	2132.38	9661.32	1932.26	952.45	1179.93
3) "traditional" schedule	12422.80	1760.55	10662.25	2132.45	617.25	1143.30
4) "4-spray"	11610.75	1560.63	10050.12	2010.02	380.80	1179.83
5) no fungicides	6947.05	1179.83	5767.22	1153.44	00.00	1179.83
LSD, P = 0.05	-	-	2179.40	-	-	-

Table A5. Revenue, cost and return per season for a 4-hectare (10 acres) orchard size, 1989

treatment	total revenue per 4 hectares	total cost per 4 hectares	total return per 4 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 4 hectares	
					apple scab	codling moth
1) Predictor	14447.40	3293.22	11154.18	1115.42	2645.87	647.35
2) Leaf Wetness Recorder	14030.50	2354.95	11675.55	1167.56	1707.6	647.35
3) "traditional" schedule	16013.20	2737.70	13275.50	1327.55	1377.60	1360.10
4) "4-spray"	11194.70	1784.85	9409.85	940.99	969.80	815.05
5) no fungicides	11713.40	815.055	10898.35	1089.84	00.00	815.055
LSD, P = 0.05	-	-	1306.80	-	-	

Table A6. Revenue, cost and return per season for a 4-hectare (10 acres) orchard size, 1990

treatment	total revenue per 4 hectares	total cost per 4 hectares	total return per 4 hectares	return per 0.4 hectares (1 acre)	control cost per pest per 4 hectares	
					apple scab	codling moth
1) CR-10	33428.30	3447.98	29980.32	2998.03	1105.43	2342.55
2) Leaf Wetness Recorder	23587.40	3634.05	19953.35	1995.34	1291.50	2342.55
3) "traditional" schedule	24845.60	3521.10	21324.50	2132.45	1234.50	2286.60
4) "4-spray"	23221.50	3104.15	20117.35	2011.74	761.60	2342.55
5) no fungicides	13894.10	2342.55	11551.55	1155.16	00.00	2342.55
LSD, P = 0.05	-	-	4358.90	-	-	-

Table A7. Revenue, cost and return per season for a 8-hectare (20 acres) orchard size, 1989

treatment	total revenue per 8 hectares	total cost per 8 hectares	total return per 8 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 8 hectares	
					apple scab	codling moth
1) Predictor	28894.80	5398.84	23495.96	1174.80	4104.14	1294.70
2) Leaf Wetness Recorder	28061.00	4096.50	23964.5	1198.23	2801.80	1294.70
3) "traditional" schedule	32026.40	5475.40	26551.00	1327.55	2755.20	2720.20
4) "4-spray"	22389.40	3543.00	18846.40	942.32	1939.60	1603.40
5) no fungicides	23428.00	1603.40	21824.60	1091.23	00.00	1603.40
LSD, P = 0.05	-	-	2613.60	-	-	-

Table A8. Revenue, cost and return per season for a 8-hectare (20 acres) orchard size, 1990

treatment	total revenue per 8 hectares	total cost per 8 hectares	total return per 8 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 8 hectares	
					apple scab	codling moth
1) CR-10	66856.60	6468.63	60387.97	3019.40	1783.53	4685.10
2) Leaf Wetness Recorder	47174.80	6654.70	40520.10	2026.01	1969.60	4685.10
3) "traditional" schedule	49691.20	7042.20	42649.00	2132.45	2469.00	4573.20
4) "4-spray"	46443.00	6208.30	40234.70	2011.74	1523.20	4685.10
5) no fungicides	27788.20	4685.10	23103.10	1155.16	00.00	4685.10
LSD, P = 0.05	-	-	8425.80	-	-	-

Table A9. Revenue, cost and return per season for a 16-hectare (40 acres) orchard size, 1989

treatment	total revenue per 16 hectares	total cost per 16 hectares	total return per 16 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 16 hectares	
					apple scab	codling moth
1) Predictor	57789.60	9610.08	48179.52	1204.49	7020.68	2589.40
2) Leaf Wetness Recorder	56122.00	7579.60	48542.40	1213.56	4990.20	2589.40
3) "traditional" schedule	64052.80	10950.80	53102.00	1327.55	5510.40	5440.40
4) "4-spray"	44778.80	7059.30	37719.50	942.98	3879.20	3180.10
5) no fungicides	46853.60	3180.10	43673.50	1091.84	00.00	3180.10
LSD, P = 0.05	-	-	5227.10	-	-	-

Table A10. Revenue, cost and return per season for a 16-hectare (40 acres) orchard size, 990

treatment	total revenue per 16 hectares	total cost per 16 hectares	total return per 16 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 16 hectares	
					apple scab	codling moth
1) CR-10	133713.20	12509.93	121203.27	3030.08	3139.73	9370.20
2) Leaf Wetness Recorder	94349.60	12696.00	81653.60	2041.34	3325.80	9370.20
3) "traditional" schedule	99382.40	14084.40	85298.00	2132.45	4938.00	9146.40
4) "4-spray"	92886.00	12416.60	80469.40	2011.74	3046.40	9370.20
5) no fungicides	55576.40	9370.20	46206.20	1155.16	00.00	9370.20
LSD, P = 0.05	-	-	17435.00	-	-	-

Table All. Revenue, cost and return per both seasons (1989 +1990) for a 2-hectare (5 acres) orchard size

treatment	total revenue per 2 hectares	total cost per 2 hectares	total return per 2 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 2 hectares	
					apple scab	codling moth
1) Predictor and CR-10	23037.85	4195.38	18842.47	3768.49	2683.12	1512.26
2) Leaf Wetness Recorder	18808.95	3625.21	15183.74	3036.75	2112.95	1512.26
3) "traditional" schedule	20429.40	3129.40	17300.00	3460.00	1306.05	1823.35
4) "4-spray"	17208.10	2501.77	14706.33	2941.27	865.70	1636.06
5) no fungicides	12803.75	1636.06	11167.69	2233.54	00.00	1636.06
LSD, P = 0.05	-	-	2638.40	-	-	-

Table A12. Revenue, cost and return per both seasons (1989 + 1990) for a 4-hectare (10 acres) orchard size

treatment	total revenue per 4 hectares	total cost per 4 hectares	total return per 4 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 4 hectares	
					apple scab	codling moth
1) Predictor and CR-10	47875.70	6741.20	41134.50	4113.45	3751.30	2989.90
2) Leaf Wetness Recorder	37617.90	5989.00	31628.90	3162.89	2999.10	2989.90
3) "traditional" schedule	40858.80	6258.80	34600.00	3460.00	2612.10	3646.70
4) "4-spray"	34416.20	4915.70	29500.50	2950.05	1731.40	3184.30
5) no fungicides	25607.50	3184.30	22423.20	2242.32	00.00	3184.30
LSD, P = 0.05	-	-	5190.30	-	-	-

Table A13. Revenue, cost and return per both seasons (1989 + 1990) for a 8-hectare (20 acres) orchard size

treatment	total revenue per 8 hectares	total cost per 8 hectares	total return per 8 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 8 hectares	
					apple scab	codling moth
1) Predictor and CR-10	95751.40	11867.47	83883.93	4194.20	5887.67	5979.80
2) Leaf Wetness Recorder	75235.80	10751.20	64484.60	3224.23	4771.40	5979.80
3) "traditional" schedule	81717.60	12517.60	69200.00	3460.00	5224.20	7293.40
4) "4-spray"	68832.40	9778.80	59054.40	2952.72	3462.80	6315.20
5) no fungicides	51216.20	6315.20	44901.00	2246.97	00.00	6315.20
LSD, P = 0.05	-	-	11158.00	-	-	-

Table A14. Revenue, cost and return per both seasons (1989 + 1990) for a 16-hectare (40 acres) orchard size

treatment	total revenue per 16 hectares	total cost per 16 hectares	total return per 16 hectares	return per 0.4 hectare (1 acre)	control cost per pest per 16 hectares	
					apple scab	codling moth
1) Predictor and CR-10	191502.80	22120.01	169382.79	4234.57	10160.41	11959.60
2) Leaf Wetness Recorder	150471.60	20275.60	130196.00	3254.90	8316.00	11959.60
3) "traditional" schedule	163435.20	25035.20	138400.00	3460.00	10448.40	14586.80
4) "4-spray"	137664.80	19502.60	118162.20	2954.06	6925.60	12577.00
5) no fungicides	102430.00	12550.30	89819.70	2246.99	00.00	12550.30
LSD, P = 0.05	-	-	24269.85	-	-	-

Economic Analysis Calculations - 1989

Costs for treatment 1

A. Apple scab

I. Machinery costs (tractor + sprayer). The fixed cost for machinery per season per ha is \$7.875 (M. Duffy, Department of Economics, Iowa State University, Ames, Iowa, personal communication. Total machinery cost per season per haectare is equal to yearly fixed cost per ha x number of sprays x orchard size (ha). This equation will be used in all treatments and will not be repeated in each treatment.

Total machinery cost

$$\begin{aligned}
 &= \$7.875 \times 4 \times 2 = \$63.00 \text{ /year for a 2-ha orchard} \\
 &= \$7.875 \times 4 \times 4 = \$126.00/\text{year for a 4-ha orchard} \\
 &= \$7.875 \times 4 \times 8 = \$252.00/\text{year for an 8-ha orchard} \\
 &= \$7.875 \times 4 \times 16 = \$504.00/\text{year for a 16-ha orchard}
 \end{aligned}$$

II. Labor cost per season = (time to monitor the Predictor + time to spray) x labor cost per hour (\$6.00) =

$$\begin{aligned}
 (5.1 + 6) \times \$6.00 &= \$66.60/\text{year for a 2-ha orchard} \\
 (5.1 + 12) \times \$6.00 &= \$102.60/\text{year for a 4-ha orchard} \\
 (5.1 + 24) \times \$6.00 &= \$174.60/\text{year for an 8-ha orchard} \\
 (5.1 + 48) \times \$6.00 &= \$318.60/\text{year for a 16-ha orchard}
 \end{aligned}$$

III. Weather monitoring equipment cost (Predictor) = (Predictor initial price x amortization per year) + yearly repair and maintenance = $(3980 \times 0.15) + 560 = \$1157.00/\text{year}$. This cost is fixed for orchard size up to 16 ha because this instrument provides adequate cover for up to 16 ha.

IV. Chemical costs = chemical cost per ha x orchard size =

$$126.027 \times 5 = \$630.14/\text{year for a 2-ha orchard}$$

$$126.027 \times 10 = \$1260.27/\text{year for a 4-ha orchard}$$

$$126.027 \times 20 = \$2520.54/\text{year for an 8-ha orchard}$$

$$126.027 \times 40 = \$5041.08/\text{year for a 16-ha orchard}$$

B. Codling moth

I. Machinery cost =

$$7.875 \times 4 \times 2 = \$63.00 / \text{year for a 2-ha orchard}$$

$$7.875 \times 4 \times 4 = \$126.00/\text{year for a 4-ha orchard}$$

$$7.875 \times 4 \times 8 = \$252.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 4 \times 16 = \$504.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the traps) x labor per hour =

$$12 \times 6 = \$72.00/\text{year for a 2-ha orchard}$$

$$22 \times 6 = \$132.00/\text{year for a 4-ha orchard}$$

$$44 \times 6 = \$264.00/\text{year for an 8-ha orchard}$$

$$88 \times 6 = \$528.00/\text{year for a 16-ha orchard}$$

III. Chemical costs = chemical cost per ha x orchard size

$$36.28 \times 5 = \$181.40/\text{year for a 2-ha orchard}$$

$$36.28 \times 10 = \$362.80/\text{year for a 4-ha orchard}$$

$$36.28 \times 20 = \$725.60/\text{year for an 8-ha orchard}$$

$$36.28 \times 40 = \$1451.20/\text{year for a 16-ha orchard}$$

IV. Trap cost per season = number of trap sets x price per set =

$$3 \times 5.31 = \$15.93/\text{year for a 2-ha orchard}$$

$$5 \times 5.31 = \$26.55/\text{year for a 4-ha orchard}$$

$$10 \times 5.31 = \$53.10/\text{year for an 8-ha orchard}$$

$$20 \times 5.31 = \$106.20/\text{year for a 16-ha orchard}$$

All equations used in treatment 1 will be applied directly for treatments 2, 3, 4 and 5 unless noted otherwise.

Costs for treatment 2

A. Apple scab

I. Machinery cost per season =

$$7.875 \times 3 \times 2 = \$47.25 / \text{year for a 2-ha orchard}$$

$$7.875 \times 3 \times 4 = \$94.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 3 \times 8 = \$189.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 3 \times 16 = \$378.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the Leaf Wetness Recorder (LWR)) x labor cost per hour =

$$10.9 \times 6 = \$65.40/\text{year for a 2-ha orchard}$$

$$15.4 \times 6 = \$92.40/\text{year for a 4-ha orchard}$$

$$24.4 \times 6 = \$146.40/\text{year for an 8-ha orchard}$$

$$42.4 \times 6 = \$254.40/\text{year for a 16-ha orchard}$$

III. LWR cost per season = (LWR initial price x amortization per year) + yearly repair and maintenance =

$(2300 \times 0.15) + 230 = \$575.00/\text{year}$. This cost is fixed for orchard sizes up to 16 ha because the LWR provides adequate cover for up to 16 ha.

IV. Chemical cost per season =

$$94.57 \times 5 = \$472.85/\text{year for a 2-ha orchard}$$

$$94.57 \times 10 = \$945.70/\text{year for a 4-ha orchard}$$

$$94.57 \times 20 = \$1891.40/\text{year for an 8-ha orchard}$$

$$94.57 \times 40 = \$3782.80/\text{year for a 16-ha orchard}$$

B. Codling moth

I. Machinery cost per season =

$$7.875 \times 4 \times 2 = \$63.00/\text{year for a 2-ha orchard}$$

$$7.875 \times 4 \times 4 = \$126.00/\text{year for a 4-ha orchard}$$

$$7.875 \times 4 \times 8 = \$252.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 4 \times 16 = \$504.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the traps) x labor cost per hour =

$$12 \times 6 = \$72.00/\text{year for a 2-ha orchard}$$

$$22 \times 6 = \$132.00/\text{year for a 4-ha orchard}$$

$$44 \times 6 = \$264.00/\text{year for an 8-ha orchard}$$

$$88 \times 6 = \$528.00/\text{year for a 16-ha orchard}$$

III. Chemical cost per season =

$$36.28 \times 5 = \$181.40/\text{year for a 2-ha orchard}$$

$$36.28 \times 10 = \$362.80/\text{year for a 4-ha orchard}$$

$$36.28 \times 20 = \$725.60/\text{year for an 8-ha orchard}$$

$$36.28 \times 40 = \$1451.20/\text{year for a 16-ha orchard}$$

IV. Trap cost per season = number of trap sets x price per set =

$$3 \times 5.31 = \$15.93/\text{year for a 2-ha orchard}$$

$5 \times 5.31 = \$26.55/\text{year}$ for a 4-ha orchard

$10 \times 5.31 = \$53.10/\text{year}$ for an 8-ha orchard

$20 \times 5.31 = \$106.20/\text{year}$ for a 16-ha orchard

Costs for treatment 3

A. Apple scab

I. Machinery cost per season =

$7.875 \times 7 \times 2 = \$110.25/\text{year}$ for a 2-ha orchard

$7.875 \times 7 \times 4 = \$220.50/\text{year}$ for a 4-ha orchard

$7.875 \times 7 \times 8 = \$441.00/\text{year}$ for an 8-ha orchard

$7.875 \times 7 \times 16 = \$882.00/\text{year}$ for a 16-ha orchard

II. Labor cost per season = time to spray \times labor cost per hour =

$10.5 \times 6 = \$63.00/\text{year}$ for a 2-ha orchard

$21 \times 6 = \$126.00/\text{year}$ for a 4-ha orchard

$42 \times 6 = \$252.00/\text{year}$ for an 8-ha orchard

$84 \times 6 = \$504.00/\text{year}$ for a 16-ha orchard

III. Chemical cost per season =

$103.11 \times 5 = \$515.55/\text{year}$ for a 2-ha orchard

$103.11 \times 10 = \$1031.10/\text{year}$ for a 4-ha orchard

$103.11 \times 20 = \$2062.20/\text{year}$ for an 8-ha orchard

$103.11 \times 40 = \$4124.40/\text{year}$ for a 16-ha orchard

B. Codling moth

I. Machinery cost per season =

$7.875 \times 9 \times 2 = \$141.75/\text{year}$ for a 2-ha orchard

$$7.875 \times 4 = \$283.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 9 \times 8 = \$567.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 9 \times 16 = \$1134.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = time to spray x labor cost per hour =

$$13.5 \times 6 = \$81.00/\text{year for a 2-ha orchard}$$

$$27 \times 6 = \$162.00/\text{year for a 4-ha orchard}$$

$$54 \times 6 = \$324.00/\text{year for an 8-ha orchard}$$

$$108 \times 6 = \$648.00/\text{year for a 16-ha orchard}$$

III. Chemical cost per season =

$$91.46 \times 5 = \$457.30/\text{year for a 2-ha orchard}$$

$$91.46 \times 10 = \$914.60/\text{year for a 4-ha orchard}$$

$$91.46 \times 20 = \$1829.20/\text{year for an 8-ha orchard}$$

$$91.46 \times 40 = \$3658.40/\text{year for a 16-ha orchard}$$

Costs for treatment 4

A. Apple scab

I. Machinery cost per season =

$$7.875 \times 4 \times 2 = \$63.00/\text{year for a 2-ha orchard}$$

$$7.875 \times 4 \times 4 = \$126.00/\text{year for a 4-ha orchard}$$

$$7.875 \times 4 \times 8 = \$252.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 4 \times 16 = \$504.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = time to spray x labor cost per hour =

$$6 \times 6 = \$36.00/\text{year for a 2-ha orchard}$$

$$12 \times 6 = \$72.00/\text{year for a 4-ha orchard}$$

$24 \times 6 = \$144.00/\text{year}$ for an 8-ha orchard

$48 \times 6 = \$288.00/\text{year}$ for a 16-ha orchard

III. Chemical cost per season =

$77.18 \times 5 = 385.90/\text{year}$ for a 2-ha orchard

$77.18 \times 10 = \$771.80/\text{year}$ for a 4-ha orchard

$77.18 \times 20 = \$1543.60/\text{year}$ for an 8-ha orchard

$77.18 \times 40 = \$3087.20/\text{year}$ for a 16-ha orchard

B. Codling moth

I. Machinery cost per season =

$7.875 \times 5 \times 2 = \$78.75/\text{year}$ for a 2-ha orchard

$7.875 \times 5 \times 4 = \$157.50/\text{year}$ for a 4-ha orchard

$7.875 \times 5 \times 8 = \$315.00/\text{year}$ for an 8-ha orchard

$7.875 \times 5 \times 16 = \$630.00/\text{year}$ for a 16-ha orchard

II. Labor cost per season = (time to spray + time to monitor the traps + time to monitor the max/min thermometer and calculate degree-days) x labor cost per hour =

$16.70 \times 6 = \$100.20/\text{year}$ for a 2-ha orchard

$28.20 \times 6 = \$169.20/\text{year}$ for a 4-ha orchard

$53.20 \times 6 = \$319.20/\text{year}$ for an 8-ha orchard

$103.20 \times 6 = \$619.20/\text{year}$ for a 16-ha orchard

III. Chemical cost per season =

$45.43 \times 5 = \$227.15/\text{year}$ for a 2-ha orchard

$45.43 \times 10 = \$454.30/\text{year}$ for a 4-ha orchard

$45.43 \times 20 = \$908.60/\text{year}$ for an 8-ha orchard

$$45.20 \times 40 = \$1817.20/\text{year for a 16-ha orchard}$$

IV. Trap cost per season = number of trap sets \times price per set =

$$3 \times 5.31 = \$15.93/\text{year for a 2-ha orchard}$$

$$5 \times 5.31 = \$26.55/\text{year for a 4-ha orchard}$$

$$10 \times 5.31 = \$53.10/\text{year for an 8-ha orchard}$$

$$20 \times 5.31 = \$106.20/\text{year for a 16-ha orchard}$$

V. Temperature-monitoring equipment = (max/min thermometer initial price \times amortization per year) + yearly repair and maintenance = $(30 \times 0.15) + 3 = \$7.50$

Costs for treatment 5

A. Apple scab

This treatment did not receive any fungicides (control), so apple scab control cost is 00.00

B. Codling moth

I. Machinery cost per season =

$$7.875 \times 5 \times 2 = \$78.75 \text{ /year for a 2-ha orchard}$$

$$7.875 \times 5 \times 4 = \$157.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 5 \times 8 = \$315.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 5 \times 16 = \$630.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the traps + time to monitor the max/min thermometer and calculate degree-days) \times labor cost per hour =

$$16.70 \times 6 = \$100.20/\text{year for a 2-ha orchard}$$

$28.20 \times 6 = \$169.20/\text{year}$ for a 4-ha orchard

$53.20 \times 6 = \$319.20/\text{year}$ for an 8-ha orchard

$103.20 \times 6 = \$619.20/\text{year}$ for a 16-ha orchard

III. Chemical cost per season =

$45.43 \times 5 = \$227.15/\text{year}$ for a 2-ha orchard

$45.43 \times 10 = \$454.30/\text{year}$ for a 4-ha orchard

$45.43 \times 20 = \$908.60/\text{year}$ for an 8-ha orchard

$45.20 \times 40 = \$1817.20/\text{year}$ for a 16-ha orchard

IV. Trap cost per season = number of trap sets \times price per set =

$3 \times 5.31 = \$15.93/\text{year}$ for a 2-ha orchard

$5 \times 5.31 = \$26.55/\text{year}$ for a 4-ha orchard

$10 \times 5.31 = \$53.10/\text{year}$ for an 8-ha orchard

$20 \times 5.31 = \$106.20/\text{year}$ for a 16-ha orchard

V. Temperature-monitoring equipment per season = \$7.50 (calculated as in treatment 4).

Economic Analysis Calculations - 1990

Costs for treatment 1

A. Apple scab

I. Machinery costs (tractor + sprayer). The fixed cost for machinery per season per ha is \$7.875 (M. Duffy, Department of Economics, Iowa State University, Ames, Iowa, personal communication). Total machinery cost per season per hectare is equal to yearly fixed cost per ha \times number of sprays \times orchard size (ha). This equation will be

used in all treatments and will not be repeated in each treatment.

Total machinery cost

$$\begin{aligned}
 &= 7.875 \times 3 \times 2 = \$47.25 \text{ /year for 2-ha orchard} \\
 &= 7.875 \times 3 \times 4 = \$94.50 \text{ /year for a 4-ha orchard} \\
 &= 7.875 \times 3 \times 8 = \$189.00/\text{year for an 8-ha orchard} \\
 &= 7.875 \times 3 \times 16 = \$378.00/\text{year for a 16-ha orchard}
 \end{aligned}$$

II. Labor cost per season = (time to monitor the CR-10 + time to spray) x labor cost per hour (\$6.00) =

$$\begin{aligned}
 (6.43 + 4.5) \times 6 &= \$65.58/\text{year for a 2-ha orchard} \\
 (6.43 + 9) \times 6 &= \$92.58/\text{year for a 4-ha orchard} \\
 (6.43 + 18) \times 6 &= \$146.58/\text{year for an 8-ha orchard} \\
 (6.43 + 36) \times 6 &= \$254.58/\text{year for a 16-ha orchard}
 \end{aligned}$$

III. Weather monitoring equipment cost (CR-10) = (CR-10 initial price x amortization per year) + yearly repair and maintenance =

$$(1555 \times 0.15) + 155.50 = \$388.75. \text{ This cost is fixed for orchard size up to 16 ha because this instrument provides adequate cover for up to 16 ha.}$$

IV. Chemical costs = chemical cost per ha x orchard size =

$$\begin{aligned}
 52.96 \times 5 &= \$264.80/\text{year for a 2-ha orchard} \\
 52.96 \times 10 &= \$529.60/\text{year for a 4-ha orchard} \\
 52.96 \times 20 &= \$1059.20/\text{year for an 8-ha orchard} \\
 52.96 \times 40 &= \$2118.40/\text{year for a 16-ha orchard}
 \end{aligned}$$

B. Codling moth

I. Machinery cost =

$$7.875 \times 7 \times 2 = \$110.25/\text{year for a 2-ha orchard}$$

$$7.875 \times 7 \times 4 = \$220.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 7 \times 8 = \$441.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 7 \times 16 = \$882.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the traps) x labor per hour =

$$16.5 \times 6 = \$99.00/\text{year for a 2-ha orchard}$$

$$31 \times 6 = \$186.00/\text{year for a 4-ha orchard}$$

$$62 \times 6 = \$372.00/\text{year for an 8-ha orchard}$$

$$124 \times 6 = \$744.00/\text{year for a 16-ha orchard}$$

III. Chemical costs = chemical cost per ha x orchard size

$$190.95 \times 5 = \$954.75/\text{year for a 2-ha orchard}$$

$$190.95 \times 10 = \$1909.50/\text{year for a 4-ha orchard}$$

$$190.95 \times 20 = \$3819.00/\text{year for an 8-ha orchard}$$

$$190.95 \times 40 = \$7638.00/\text{year for a 16-ha orchard}$$

IV. Trap cost per season = number of trap sets x price per set =

$$3 \times 5.31 = \$15.93/\text{year for a 2-ha orchard}$$

$$5 \times 5.31 = \$26.55/\text{year for a 4-ha orchard}$$

$$10 \times 5.31 = \$53.10/\text{year for an 8-ha orchard}$$

$$20 \times 5.31 = \$106.20/\text{year for a 16-ha orchard}$$

All equations used in treatment 1 will be applied directly for treatments 2, 3, 4 and 5 unless noted otherwise.

Costs for treatment 2

A. Apple scab

I. Machinery cost per season =

$$7.875 \times 3 \times 2 = \$47.25 \text{ /year for a 2-ha orchard}$$

$$7.875 \times 3 \times 4 = \$94.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 3 \times 8 = \$189.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 3 \times 16 = \$378.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the Leaf

Wetness Recorder (LWR)) x labor cost per hour =

$$10.9 \times 6 = \$65.40/\text{year for a 2-ha orchard}$$

$$15.4 \times 6 = \$92.40/\text{year for a 4-ha orchard}$$

$$24.4 \times 6 = \$146.40/\text{year for an 8-ha orchard}$$

$$42.4 \times 6 = \$254.40/\text{year for a 16-ha orchard}$$

III. LWR cost per season = (LWR initial price x amortization per year)

+ yearly repair and maintenance =

$(2300 \times 0.15) + 230 = \$575.00/\text{year}$. This cost is fixed for orchard sizes up to 16 ha because the LWR provides adequate cover for up to 16 ha.

IV. Chemical cost per season =

$$52.96 \times 5 = \$264.80/\text{year for a 2-ha orchard}$$

$$52.96 \times 10 = \$529.60/\text{year for a 4-ha orchard}$$

$$52.96 \times 20 = \$1059.20/\text{year for an 8-ha orchard}$$

$$52.96 \times 40 = \$2118.40/\text{year for a 16-ha orchard}$$

B. codling moth

I. Machinery cost =

$$7.875 \times 7 \times 2 = \$110.25/\text{year for a 2-ha orchard}$$

$$7.875 \times 7 \times 4 = \$220.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 7 \times 8 = \$441.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 7 \times 16 = \$882.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the traps) x labor per hour =

$$16.5 \times 6 = \$99.00/\text{year for a 2-ha orchard}$$

$$31 \times 6 = \$186.00/\text{year for a 4-ha orchard}$$

$$62 \times 6 = \$372.00/\text{year for an 8-ha orchard}$$

$$124 \times 6 = \$744.00/\text{year for a 16-ha orchard}$$

III. Chemical costs = chemical cost per ha x orchard size

$$190.95 \times 5 = \$954.75/\text{year for a 2-ha orchard}$$

$$190.95 \times 10 = \$1909.50/\text{year for a 4-ha orchard}$$

$$190.95 \times 20 = \$3819.00/\text{year for an 8-ha orchard}$$

$$190.95 \times 40 = \$7638.00/\text{year for a 16-ha orchard}$$

IV. Trap cost per season = number of trap sets x price per set =

$$3 \times 5.31 = \$15.93/\text{year for a 2-ha orchard}$$

$$5 \times 5.31 = \$26.55/\text{year for a 4-ha orchard}$$

$$10 \times 5.31 = \$53.10/\text{year for an 8-ha orchard}$$

$$20 \times 5.31 = \$106.20/\text{year for a 16-ha orchard}$$

Costs for treatment 3

A. Apple scab

I. Machinery cost per season =

$$7.875 \times 7 \times 2 = \$110.25 \text{ /year for a 2-ha orchard}$$

$$7.875 \times 7 \times 4 = \$220.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 7 \times 8 = \$441.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 7 \times 16 = \$882.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = time to spray x labor cost per hour =

$$10.5 \times 6 = \$63.00/\text{year for a 2-ha orchard}$$

$$21 \times 6 = \$126.00/\text{year for a 4-ha orchard}$$

$$42 \times 6 = \$252.00/\text{year for an 8-ha orchard}$$

$$84 \times 6 = \$504.00/\text{year for a 16-ha orchard}$$

III. Chemical cost per season =

$$88.80 \times 5 = \$444.00/\text{year for a 2-ha orchard}$$

$$88.80 \times 10 = \$888.00/\text{year for a 4-ha orchard}$$

$$88.80 \times 20 = \$1776.00/\text{year for an 8-ha orchard}$$

$$88.80 \times 40 = \$3552.00/\text{year for a 16-ha orchard}$$

B. Codling moth

I. Machinery cost per season =

$$7.875 \times 9 \times 2 = \$141.75 \text{ /year for a 2-ha orchard}$$

$$7.875 \times 9 \times 4 = \$283.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 9 \times 8 = \$567.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 9 \times 16 = \$1134.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = time to spray x labor cost per hour =

$13.5 \times 6 = \$81.00/\text{year}$ for a 2-ha orchard

$27 \times 6 = \$162.00/\text{year}$ for a 4-ha orchard

$54 \times 6 = \$324.00/\text{year}$ for an 8-ha orchard

$108 \times 6 = \$638.00/\text{year}$ for a 16-ha orchard

III. Chemical cost per season =

$184.11 \times 5 = \$920.55/\text{year}$ for a 2-ha orchard

$184.11 \times 10 = \$1841.10/\text{year}$ for a 4-ha orchard

$184.11 \times 20 = \$3682.20/\text{year}$ for an 8-ha orchard

$184.11 \times 40 = \$7364.40/\text{year}$ for a 16-ha orchard

Costs for treatment 4

A. Apple scab

I. Machinery cost per season =

$7.875 \times 3 \times 2 = \$47.25/\text{year}$ for a 2-ha orchard

$7.875 \times 3 \times 4 = \$94.50/\text{year}$ for a 4-ha orchard

$7.875 \times 3 \times 8 = \$189.00/\text{year}$ for an 8-ha orchard

$7.875 \times 3 \times 16 = \$378.00/\text{year}$ for a 16-ha orchard

II. Labor cost per season = time to spray x labor cost per hour =

$4.5 \times 6 = \$27.00/\text{year}$ for a 2-ha orchard

$9 \times 6 = \$54.00/\text{year}$ for a 4-ha orchard

$18 \times 6 = \$108.00/\text{year}$ for an 8-ha orchard

$36 \times 6 = \$216.00/\text{year}$ for a 16-ha orchard

III. Chemical cost per season =

$61.31 \times 5 = 306.55/\text{year}$ for a 2-ha orchard

$61.31 \times 10 = \$613.10/\text{year}$ for a 4-ha orchard

$61.31 \times 20 = \$1226.20/\text{year}$ for an 8-ha orchard

$61.31 \times 40 = \$2452.40/\text{year}$ for a 16-ha orchard

B. Codling moth

I. Machinery cost =

$7.875 \times 7 \times 2 = \$110.25/\text{year}$ for a 2-ha orchard

$7.875 \times 7 \times 4 = \$220.50/\text{year}$ for a 4-ha orchard

$7.875 \times 7 \times 8 = \$441.00/\text{year}$ for an 8-ha orchard

$7.875 \times 7 \times 16 = \$882.00/\text{year}$ for a 16-ha orchard

II. Labor cost per season = (time to spray + time to monitor the traps) x labor per hour =

$16.5 \times 6 = \$99.00/\text{year}$ for a 2-ha orchard

$31 \times 6 = \$186.00/\text{year}$ for a 4-ha orchard

$62 \times 6 = \$372.00/\text{year}$ for an 8-ha orchard

$124 \times 6 = \$744.00/\text{year}$ for a 16-ha orchard

III. Chemical costs = chemical cost per ha x orchard size

$190.95 \times 5 = \$954.75/\text{year}$ for a 2-ha orchard

$190.95 \times 10 = \$1909.50/\text{year}$ for a 4-ha orchard

$190.95 \times 20 = \$3819.00/\text{year}$ for an 8-ha orchard

$190.95 \times 40 = \$7638.00/\text{year}$ for a 16-ha orchard

IV. Trap cost per season = number of trap sets x price per set =

$3 \times 5.31 = \$15.93/\text{year}$ for a 2-ha orchard

$5 \times 5.31 = \$26.55/\text{year}$ for a 4-ha orchard

$10 \times 5.31 = \$53.10/\text{year}$ for an 8-ha orchard

$$20 \times 5.31 = \$106.20/\text{year for a 16-ha orchard}$$

Costs for treatment 5

A. Apple scab

This treatment did not receive any fungicides (control), so apple scab control cost is 00.00

B. codling moth

I. Machinery cost =

$$7.875 \times 7 \times 2 = \$110.25/\text{year for a 2-ha orchard}$$

$$7.875 \times 7 \times 4 = \$220.50/\text{year for a 4-ha orchard}$$

$$7.875 \times 7 \times 8 = \$441.00/\text{year for an 8-ha orchard}$$

$$7.875 \times 7 \times 16 = \$882.00/\text{year for a 16-ha orchard}$$

II. Labor cost per season = (time to spray + time to monitor the traps) x labor per hour =

$$16.5 \times 6 = \$99.00/\text{year for a 2-ha orchard}$$

$$31 \times 6 = \$186.00/\text{year for a 4-ha orchard}$$

$$62 \times 6 = \$372.00/\text{year for an 8-ha orchard}$$

$$124 \times 6 = \$744.00/\text{year for a 16-ha orchard}$$

III. Chemical costs = chemical cost per ha x orchard size

$$190.95 \times 5 = \$954.75/\text{year for a 2-ha orchard}$$

$$190.95 \times 10 = \$1909.50/\text{year for a 4-ha orchard}$$

$$190.95 \times 20 = \$3819.00/\text{year for an 8-ha orchard}$$

$$190.95 \times 40 = \$7638.00/\text{year for a 16-ha orchard}$$

IV. Trap cost per season = number of trap sets x price per set =

3 x 5.31 = \$15.93/year for a 2-ha orchard

5 x 5.31 = \$26.55/year for a 4-ha orchard

10 x 5.31 = \$53.10/year for an 8-ha orchard

20 x 5.31 = \$106.20/year for a 16-ha orchard